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ROTARY PUMPS.

BY RONALD J. SWEENEY.*

DEFINITION.

Rotary positive—displacement pumps are defined as mechanisms which displace a constant volume of fluid from the suction to the discharge port for each revolution of the driving shaft and in which the principal motion of the pumping elements is pure rotation. This excludes reciprocating and centrifugal types. Constant displacement does not mean constant delivery since there is always some slip back through the mechanical clearances of the pump. The pressure developed by a rotary pump is determined by the resistance of the external piping and static head, but is limited by the driving power, the slip, the bearing limitations and the mechanical strength of the pump. Rotary pumps are self-priming. The same mechanisms may be used for vacuum pumps, hydraulic motors, compressors and fluid meters with minor modifications.

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USEFULNESS.

The proper field of application for rotary pumps is for high viscosity, small volume, moderate pressure, or where their self-priming or constant-delivery characteristics are desirable. They can not compete with centrifugal pumps for large volume, low pressure, low viscosity applications. The reciprocating type is more adaptable to high pressure service. In small sizes, the rotary pump is more efficient than the centrifugal, even for low pressures and viscosities. As compared to the reciprocating type, the rotary is valveless, it can be run at higher speeds and is usually smaller, lighter and cheaper. The smaller sizes of rotary pumps can be direct-connected to standard speed electric motors.

A rotary pump can be designed to pump any material that will flow into the suction port, including gas, vapor, liquid, suspension, gel or powder. Rotary pumps are used in large quantities for circulating lubricating oil to the bearings of engines, turbines and other machinery; supplying fuel oil to oil burners and diesel engines; pumping petroleum and its products through pipe lines, loading and unloading tank ships and cars, through refinery processes and in distribution and dispensing; providing hydraulic pressure for presses, machine tools and automatic control systems; circulating cutting fluids for machine tools; and pumping water for marine engine cooling, car washing and fire service.

CLASSIFICATION.

Almost all rotary pumps may be classified into three general types of mechanisms: gear, screw and vane. The gear and multiple screw types are pure rotaries, while the vane and single screw types involve reciprocation or oscillation of the working parts.

GEAR PUMPS.

A simple type of gear pump is shown in Figure 1. The essential elements include a pair of mating gears, a closely fitting cylinder, gear shaft bearings and a drive shaft stuffing box. The gears must have at least two teeth for sealing, while seven is about the minimum number for efficient power transfer to the idler. For standard gear tooth forms a small number of teeth increases the

displacement for a given outside diameter of the gear, while a larger number reduces the flow pulsation and the slip. A 28 degree pressure angle involute system is usually employed, instead of the common power transmission systems, because it permits the operation of a smaller number of teeth. Some designs use teeth of forms designed for greater displacement, but these usually have the disadvantage of requiring timing gears for power transmission. The objective here is to obtain the maximum ratio of displacement to gear volume, without developing excessive noise or contact pressure and while retaining a reasonable gear efficiency. For standard involute teeth, this ratio of displacement to volume varies from 0.69 for 7 tooth gears to 0.52 for 11 tooth gears.

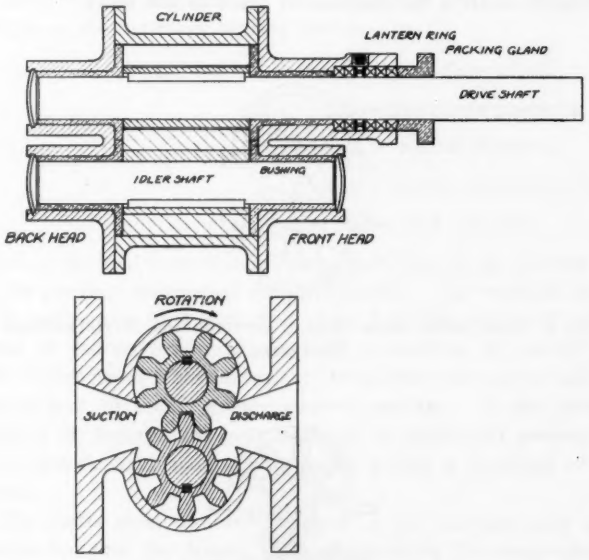

FIGURE 1. SIMPLE GEAR PUMP.

TOOTH TRAPPING.

In a spur gear pump, high local pressures are developed if liquid is compressed between the teeth as they come into mesh. These

high pressures may cause high bearings loads, tooth erosion, power loss and noise. Several methods may be used for the elimination of this trapping:

(a) Helical or herring-bone gears allow the trapped liquid to flow axially into a region of lower pressure.

(b) The discharge port may be extended in the cylinder head to the common centerline of the gears, thus providing a path from the closing tooth space to the discharge.

(c) The gears may be drilled diametrically from root to root as shown in Figure 2 or from each root to a stationary shaft groove as shown in Figure 3.

(d) The clearance and back-lash of the gears may be increased sufficiently to allow the compressed liquid to leak away.

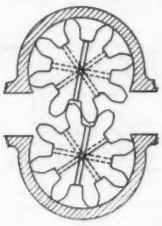

FIGURE 2. GEAR PUMP WITH RADIAL DRILLING FOR ANTI-TRAPPING AND BALANCING.

FIGURE 3. GEAR PUMP WITH TOOTH DRILLING AND SHAFT GROOVING FOR ANTI-TRAPPING.

Bearing Loads.

The bearing load in a gear pump is the resultant of that of the tooth contact pressure and the hydraulic load due to the pressure differential between the suction and discharge sides of the gears. Assuming that half the power input is transferred to the idler gear, the bearing load due to tooth contact pressure is

$P_1 = 33000\ HP \sin \theta / \pi NR$. (A) HP = horsepower input.
θ = tooth pressure angle.
N = revolutions per minute.
R = pitch radius feet.

which is directed outwardly on the common centerline of the gears.

Assuming that the pressure rises uniformly around the cylinder periphery, the hydraulic bearing load is

$P_2 = w(p_d - p_s)(d_o/\pi + d_p/2)$. (B) w = gear face width.
p_d = discharge pressure.
p_s = suction pressure.
d_o = outside diameter of gear.
d_p = pitch diameter.

which is directed from the discharge port toward the suction port on the common tangent of the pitch circles. For example, a pair of 8 tooth gears of 4 diametral pitch, 3 inches wide will deliver about 45 gallons per minute at 1150 revolutions per minute and will require about 5 horsepower at 100 pounds per square inch discharge and 10 inch mercury suction vacuum. If the pressure angle is 28 degrees, the gear load will be about 257 pounds and the hydraulic load about 566 pounds, giving a resultant of 622 pounds.

The shafts must transfer this load to the bearings with a deflection less than the desired radial clearance in the pump cylinder, minus the necessary bearing clearance.

Hydraulic Balancing.

Several schemes have beeen devised to reduce the bearing loads by hydraulic balancing. The arrangement of Figure 2 provides

partial balance by transferring discharge pressure to an area near the suction port and suction pressure to an area near the discharge port, through the radial holes. Another method, shown in Figure 4 accomplishes the same result by means of balancing ports in the cylinder heads. This method permits arbitrary choice of the location and angular width of the balance areas for the optimum reduction of the resultant load. The balance obtainable improves with the number of teeth. Comparison of Figure 4 and Figure 1 indicates the saving in shaft and bearing sizes which is permitted by hydraulic balancing. In the example, the average resultant load is reduced to 209 pounds by the balance porting shown in Figure 4. However, the slip is increased by these methods of hydraulic balancing.

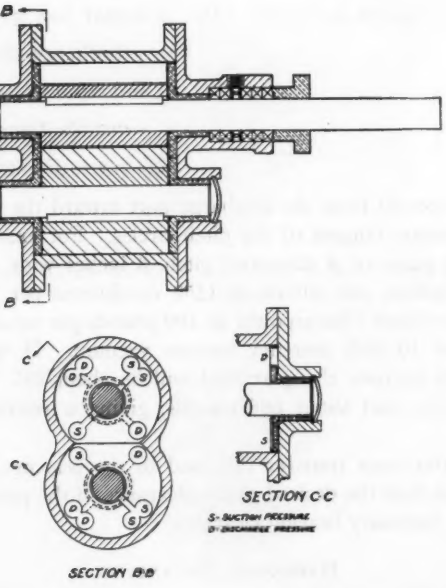

FIGURE 4. GEAR PUMP WITH CYLINDER HEAD PORTS FOR HYDRAULIC BALANCING AND BUSHING GROOVES FOR LUBRICANT CIRCULATION.

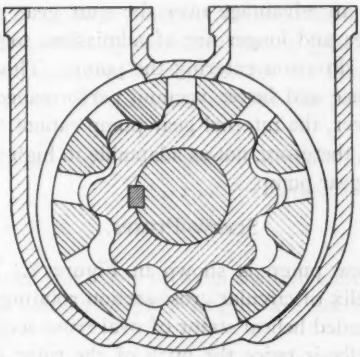

FIGURE 5. INTERNAL GEAR PUMP WITH THE RING GEAR HAVING ONE MORE TOOTH THAN THE PINION.

INTERNAL GEAR PUMPS.

Internal gear pumps are of two general types. In one type, shown in Figure 5, the ring gear has one more tooth than the pinion, and the seal is maintained by close clearance between the tips of the gear teeth on the open side. In the second type, shown in Figure 6, the ring gear has at least two more teeth than the pinion,

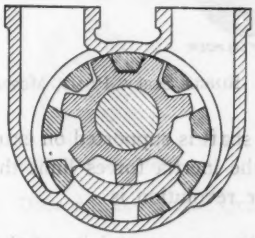

FIGURE 6. INTERNAL GEAR PUMP WITH THE RING GEAR HAVING TWO MORE TEETH THAN THE PINION.

and the seal is maintained by a stationary crescent on the open side. In either type, the fluid may enter the gear spaces axially through ports in the cylinder head or radially through ports in the ring gear. Either the ring gear or the pinion may be the idler. The internal

gear pump has an advantage over the spur gear pump in larger suction port area and longer arc of admission, together with less change of fluid direction entering the pump. This results in less suction turbulence and better vacuum performance at equal gear speeds. However, the internal gear pump cannot be hydraulically balanced and is, therefore, not as adaptable to high pressure service as the external gear pump.

Screw Pumps.

A single screw pump is shown in Figure 7. The rotor is a single-thread helix of circular cross-section rotating and oscillating in a double-threaded helical stator of oval cross-section. The pitch of the stator helix is twice the pitch of the rotor helix. At least one complete stator helix is necessary for sealing. The rotor is hollow and is driven by a connecting rod with universal joints on

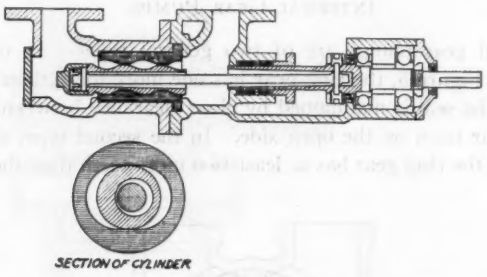

Figure 7. Single Screw Pump, Moyno Type.

each end. The drive shaft is supported on external bearings. Since the rotor oscillates, the inertia forces limit the speed of rotation. The displacement per revolution is

$$a = 4edp_s. \quad (C)$$

e = eccentricity of the rotor orbit.
d = diameter of rotor cross-section.
p_s = stator pitch.

A double screw pump is shown in Figure 8. The rotors are similar in appearance to square thread screws, but the helical mating surfaces must be concave. The discontinuous contact between

the rotors prohibits power transfer between them, so the shafts must be geared together by auxiliary timing gears. Two sets of pumping elements are usually opposed on the same shafts to balance the end thrusts. The displacement of this pump is

$$a = \pi(D^2 - d^2)\, p/4. \quad (D)$$

D = outside diameter of screws.
d = root diameter.
p = pitch.

Since a lens shaped gap exists between the two concave screw faces when meshed, a number of pitch lengths are necessary to provide adequate sealing.

A triple screw pump is shown in Figure 9. The central rotor is a double threaded helix with convex surfaces, and the idling rotors are double threaded with concave surfaces. The root of the driving screw rolls on and drives the outside diameter of the idler

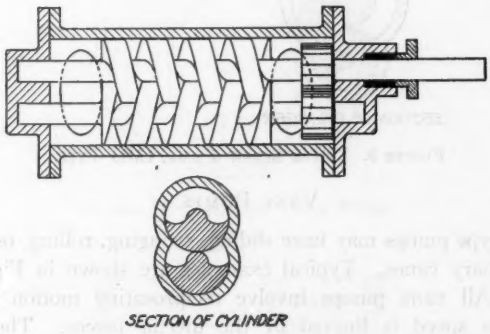

FIGURE 8. DOUBLE SCREW PUMP, QUIMBY TYPE.

screws. Adequate bearing area is provided by the outside surfaces of the screws in the cylinder. This pump is also built double-ended to balance the thrust loads.

The double and triple screw pumps are particularly adaptable to operation at high rotative speeds since the fluid velocity may be much less than the surface speed of the rotors.

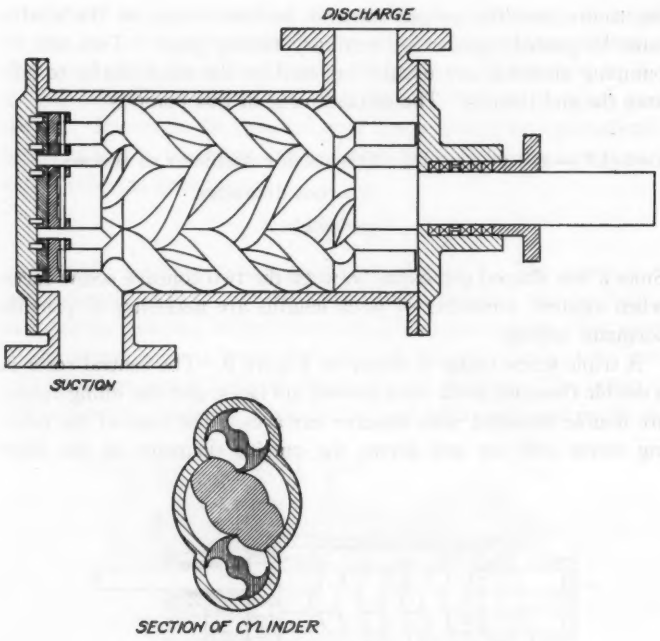

FIGURE 9. TRIPLE SCREW PUMP, IMO TYPE.

VANE PUMPS.

Vane type pumps may have sliding, swinging, rolling, oscillating or stationary vanes. Typical examples are shown in Figures 10 to 12. All vane pumps involve reciprocating motion and the maximum speed is limited by the inertia forces. The pumps shown in Figures 10, 11 and 12 are basically identical except for the form of the vanes. The essential elements are a concentric running rotor carrying reciprocating vanes which maintain contact with an eccentric cylinder. Although some pumps are built with circular cylinders, it is preferable to make the portions of the cylinders between the ports concentric with the rotor to avoid fluid compression. The portions of the cylinder in way of the ports should be a transition cam providing smooth radial acceleration and deceleration.

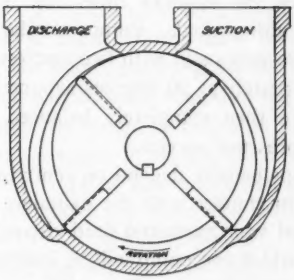

FIGURE 10. SLIDING VANE PUMP.

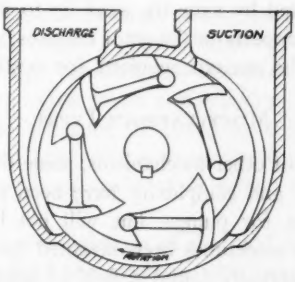

FIGURE 11. SWINGING VANE PUMP.

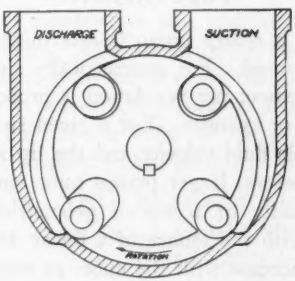

FIGURE 12. ROLLING VANE PUMP.

The bearings are subjected to a hydraulic load equal to the vertical diameter of the cylinder times the length of the rotor times the pressure differential. Pumps similar to Figure 10 are built with 8 or more vanes and with two suction and two discharge ports disposed alternately at 90 degrees around the cylinder. The hydraulic loads are then completely balanced and the pump is suitable for high pressure service.

These vane pumps usually depend on centrifugal force to maintain the vane tips in contact with the cylinder. This means that, for any condition of vane mass and fluid viscosity, there is a minimum speed below which the pump will be ineffective. These pumps are at a disadvantage when handling high viscoscity liquids, because the speed and vane weight required for sealing produce high inertia loads on the bearings. The performance of these pumps is not affected by vane tip wear up to the point when the vanes fail to seat properly in the rotor recesses, or until the weight is reduced below the amount required for centrifugal sealing.

Miscellaneous Types.

A large number of other mechanisms, some of them remarkable for their ingenuity and complexity have been proposed and used to a limited extent for pumps, but will not be described here. (1). Devices have sometimes been invented for rotary steam engines and have eventually found a field of application as pumps, compressors or fluid meters.

Pump Capacity.

The capacity of a rotary pump is determined primarily by the displacement and speed. For geometrically similar pumping elements, the displacement per revolution is proportional to the volume of the rotors or cylinder. For a given suction condition, the maximum allowable fluid velocity and the tip speed of the rotors is constant. Therefore, larger pumps must run at lower rotative speeds. The capacity of a line of geometrically similar rotary pumps increases with the square of a linear dimension, while the size and weight increase with the cube, or even worse, since the larger sizes will require reduction gears.

Slip.

Since mechanical clearances must be allowed between the rotors and the cylinder, some fluid will slip back from the discharge to the suction side of the pump, reducing the delivery below the displacement. The slip will be proportional to the square root of the pressure rise through the pump, as indicated in Figure 15, unless the viscosity is high enough to insure viscous flow through the clearance spaces. The type of flow will be affected by the velocity gradient between the rotor and cylinder. In the usual case, the slip is negligible with high viscosity liquids. The proportionality between pressure and slip will be a function of viscosity.

Cavitation.

The delivery may also be reduced by cavitation. When bubbles of air or vapor form at the pump suction, the delivery of the pump is reduced by their volume. The collapse of these bubbles when subjected to discharge pressure may result in objectionable noise and impact damage to the rotors and cylinders. Bubbles will form when the absolute pressure of the fluid entering the pumping elements is reduced below the sum of the vapor pressure of the liquid and the partial pressure of entrained or dissolved air or other gas.

If data on the vapor pressure of the fluid and the solubility of air or gas in the fluid are available, the loss of delivery due to cavitation may be calculated. Data for water are readily available (2) and some data on oils are presented in the appendix.

It is assumed that the suction reservoir is open to the atmosphere under conditions of equilibrium and that no air is mechanically entrained in the liquid. The solubility by volume of air in the liquid will be constant, so by Boyle's law, the volume released from solution by a drop in pressure, expressed as a fraction of the liquid volume, will be equal to the ratio of the pressure drop to the reduced pressure multiplied by the solubility by volume;

$$e = S(p_o - p)/p. \quad (E).$$

e = ratio of released air volume to liquid volume.
S = solubility by volume.
p_o = atmospheric pressure.
p = absolute pressure at suction.

Since all of the quantities enter as dimensionless ratios, any units may be used.

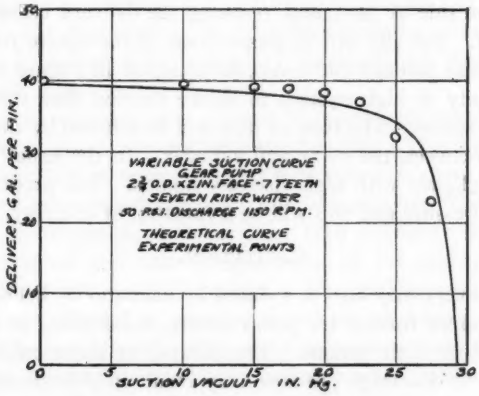

FIGURE 13. COMPARISON OF EXPERIMENTAL PERFORMANCE OF TYPICAL GEAR PUMP UNDER HIGH SUCTION VACUUM WITH PERFORMANCE PREDICTED FROM THEORY.

The absolute pressure at the suction to be used in the above expression is the available pressure as the liquid and air enter the pumping elements. It is evaluated by subtracting from the atmospheric pressure;

(1) the vapor pressure of the liquid at the suction temperature.

(2) the pressure corresponding to the maximum fluid velocity as it is picked up by the pumping elements.

(3) the suction vacuum as measured at the suction flange of the pump, which includes static suction lift and suction pipe friction. For spur gear pumps, the suction pipe velocity head need not be considered, since it will be dissipated in turbulence due to the radical change in direction from the suction pipe to the periphery of the gears. In other types of pumps, some of the suction velocity head may be conserved by careful design of the passages.

The actual delivery of the pump is given by equation (F);

$$Q = \frac{aN - b\sqrt{H}}{1+e} \quad (F)$$

Q = delivery gallons per minute.
a = displacement gallons per revolution.
b = slip factor depending on clearance and viscosity.
H = total head across pump.
e = cavitation factor from equation (E).
N = pump speed revolutions per minute.

In Figure 13 is shown a comparison of experimental data with the suction performance of a gear pump handling water as predicted by the above method.

Power Requirement.

The power required to drive a rotary pump is made up of the pressure (and possibly velocity) energy imparted to the fluid, the slip loss and mechanical and fluid friction losses. The liquid horsepower output is HW/33000, where H is total head in feet and W is delivery in pounds per minute or PQ/1714, where P is net pressure rise in pounds per square inch and Q is delivery in gallons per minute. Power is required to pump the slip in the same proportion as the delivery, so the sum of output and slip power will be PaN/1714. The friction losses will be due to Coulomb friction elements with the torque constant and the power proportional to speed, plus lubrication, fluid friction and churning elements, with the power proportional to the square of the speed. The total power input then will be;

$$HP. = PaN/1714 + k'N + k''N^2. \quad (G).$$

Both k′ and k″ will be dependent on the fluid viscosity. For perfectly lubricated sleeve bearing pumps, the friction will be independent of pressure. For ball or roller bearing pumps k′ will increase with pressure.

When a pump is tested over a range of speeds, pressures and viscosities, the data may be analysed by the help of equations (F) and (G), and the complete performance of the pump characterized

by the determination of a, b, k′ and k″ as functions of viscosity. The displacement factor a, is the slope of any capacity curve at variable speed, with the pressures and viscosity constant. The slip factor, b, for each viscosity is the slip in gallons divided by the square root of the pressure rise. To determine the power coeffi-

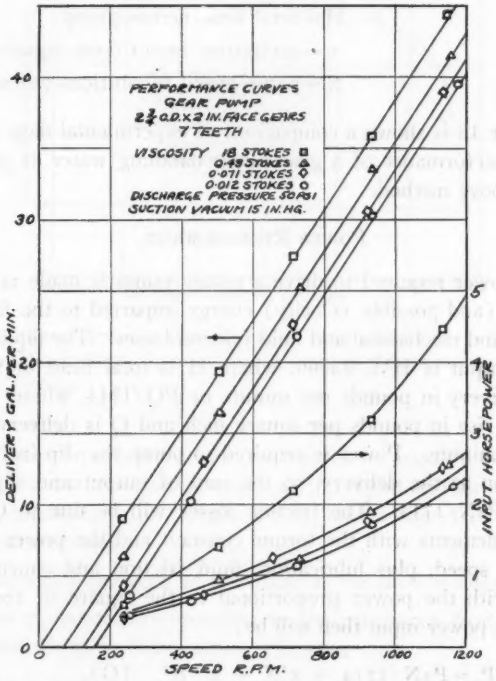

FIGURE 14. TYPICAL PERFORMANCE CURVES OF A GEAR PUMP WITH VARIABLE SPEED.

cients, PaN/1714 is subtracted from the input horsepower; the remaining friction horsepower is divided by speed and plotted against speed. The intercept on the FHP/N axis will be k′ and the slope will be k″.

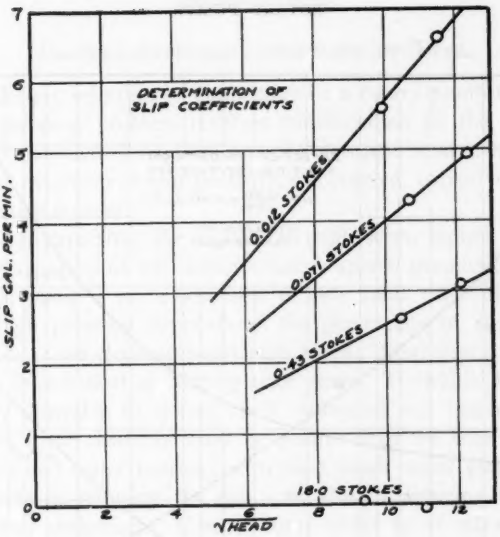

FIGURE 15. GRAPHICAL DETERMINATION OF SLIP COEFFICIENTS FROM TEST DATA.

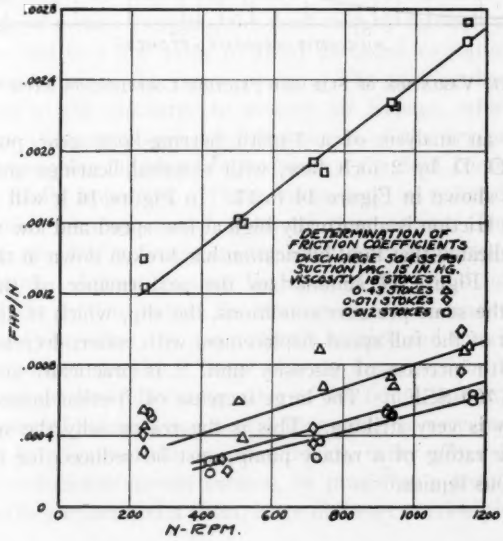

FIGURE 16. GRAPHICAL DETERMINATION OF FRICTION COEFFICIENTS.

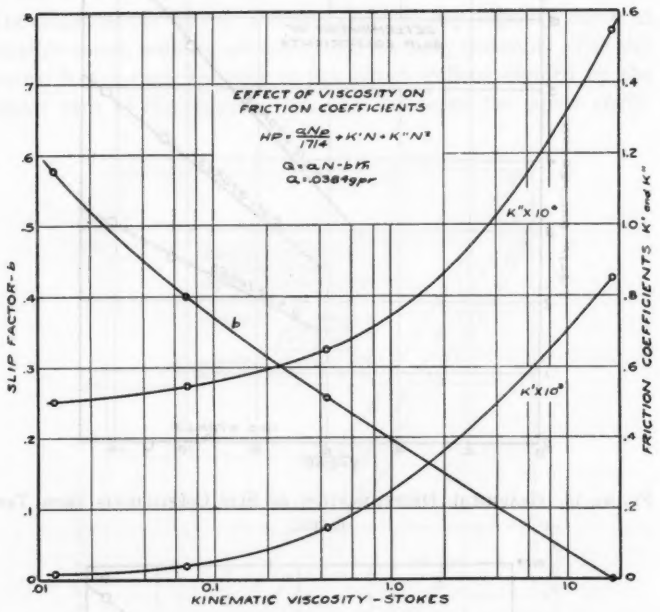

FIGURE 17. VARIATION OF SLIP AND FRICTION COEFFICIENTS WITH VISCOSITY.

Such an analysis of a 7-tooth herring-bone gear pump, 2¾ inches O. D. by 2 inch face, with external bearings and timing gears is shown in Figure 14 to 17. In Figure 16 it will be noted that the friction is abnormally high at low speed and low viscosity. This indicated that fluid lubrication has broken down at these conditions. Figure 17 summarizes the performance of the pump. Under the same pressure conditions, the slip, which is about 13.5 per cent of the full speed displacement with water, decreases regularly with increase of viscosity until it is practically zero at 18 stokes (700 SSF.). The large increase of friction losses at high viscosity is very striking. This is the reason why the speed and pressure rating of a rotary pump must be reduced for operation on viscous liquids.

Factors Affecting Selection of Type.

The design, selection or application of a rotary pump to a particular pumping problem involves consideration of the capacity, pressure and suction required and the pertinent characteristics of the liquid; viscosity, vapor pressure, gas content, corrosive activity and abrasive content.

For large capacities, the double and triple screw pumps are most adaptable because of the higher rotative speeds permissible. The spur gear pump is more adaptable to very small capacities.

For high pressure applications, the percentage of slip can be reduced by close clearances and high speed. Spur gears will have less slip than helical or herring-bone gears. Hydraulic balancing is highly desirable to reduce shaft deflection and bearing loads. Since the rotor clearance must be greater than the bearing clearance, ball and roller bearings with their small radial play are advantageous in reducing the slip, and also in reducing the shaft length and deflection. Narrow rotor width is of advantage in allowing shorter shafts of greater diameter. Gears forged integral with the shaft also reduce deflection.

For applications where the pump will be required to work against high suction vacuums, the fluid velocity through the pump must be held to a low value to avoid excessive cavitation. This requirement favors the screw pumps. The packing box should be ported to the discharge to prevent air leakage, which would cause loss of capacity and rapid destruction of the dry packing.

When pumping liquids of high viscosity, the fluid friction losses become vitally important. These losses may be reduced by low speed, wide clearances and generous port areas. The design should be checked to insure against tooth space trapping or liquid compression. Advantage may be taken of the good lubricating value of the fluid to reduce the bearing areas and bearing losses.

For low viscosities, the speed should be high and the clearances small to reduce the slip. Large bearing areas will be required, because of the low lubricating value of the liquid, and in extreme cases, external bearings and timing gears may be necessary.

When handling volatile or gassy liquids, every effort should be made to reduce the suction vacuum, by providing a positive static head on the suction, and a short, large diameter suction pipe. The

speed of the pump should be low, and the suction passages carefully designed to avoid turbulence. When the viscosity of the liquid is not excessive, a centrifugal pump may be used as a suction booster to insure pressures above atmospheric at the rotary pump suction.

For corrosive liquids it may be possible to find resistant materials of satisfactory wearing qualities, but sometimes it is more economical to use the cheapest possible pump with frequent replacement.

When abrasive materials must be handled, hard, wear-resistant metals may be used for cylinders and rotors, or easily replaceable cylinder liners, vanes or impeller wearing strips may be incorporated in the design. Rubber or synthetics are often used to advantage for abrasive materials. Clean liquid may be supplied under pressure to the bearings and packing, either from an external source or through a filter from the discharge of the pump.

Shaft Packing.

The stuffing box must be sufficiently deep to provide a long leakage path to minimize the loss of fluid. It is desirable to provide a lantern ring in the stuffing box and maintain the pressure at the lantern ring slightly above atmospheric pressure. This will minimize leakage past the gland, prevent air entering the pump and keep the packing lubricated. It may be accomplished by porting the inboard end of the packing box to discharge pressure and bleeding from the lantern ring to the suction through a relief valve set at 15 pounds per square inch or, alternatively, by porting the inboard end of the packing box to suction pressure and supplying liquid from the discharge to the lantern ring through a reducing valve set at 15 pounds per square inch. The value of 15 pounds per square inch will insure positive pressure at the lantern ring with the maximum possible suction vacuum. Rotary mechanical seals are often used in place of packing boxes. The shaft extension required for repacking the stuffing box may be reduced by the use of a split gland.

Lubrication.

Sleeve bearings should be designed to operate at a reasonable value of ZN/P with the maximum bearing loads and minimum

viscosity. For internally lubricated pumps, particularly when the bearing losses are expected to be high, definite channels should be provided to insure a positive circulation of lubricant through the bearings. The bearings will not be adequately lubricated merely by being exposed to the fluid. Timing gears and ball and roller bearings running submerged in liquid will dissipate large amounts of power. Pumps designed with external bearings and timing gears involve a multiplicity of packing boxes and fitted joints and must have long slender shafts. They are complicated and expensive and are difficult to align and repair.

When thrust loads are present because of vertical operation, hydraulic unbalance or helical gears, special thrust bearings may be necessary. If the thrust is small it may be carried on the ends of the rotors.

General Design.

It is apparent that the design of a rotary pump to meet specified conditions of pressure, suction, capacity and liquid requires the careful balance of a number of antagonistic factors. When the problem is to design a general line of pumps to work under a wide range of operating conditions, the solution necessarily involves numerous compromises. Taking gear pumps for example, if a constant number of teeth is decided on, then 3 or 4 diametral pitches will give a wide range in displacements for geometrically similar pumps. Intermediate displacements can be obtained by varying the width to diameter ratio, without much increase in tooling costs or production complexity. The bearings can be designed for the desired maximum pressure and minimum viscosity, and the drive shaft proportioned for the maximum viscosity. Each size of pump can be given a rating under these conditions for standard motor speeds.

For aid in operating and maintaining the pump in service, suction and discharge gage taps, easily accessible packing boxes and a prominent name plate giving full information on the limitations of the pump and essential lubrication instructions are all highly desirable. For large pumps, it is desirable to provide for replacing the bearings, rotors, liners and shafts without disturbing the piping, mounting or drive.

Application.

Proper application can greatly increase the value of a pump to the user. Speed, axial clearance, sealing arrangement, and suction and discharge piping are usually under the control of the application engineer. These factors can be modified to give the optimum performance under the conditions of capacity, pressure suction and fluid encountered on each particular job.

Acknowledgment.

Acknowledgment is due to the principal manufacturers of rotary pumps, from whose products most of the ideas incorporated in the paper have been gleaned; to Dr. H. S. Bean of the National Bureau of Standards for the data on oils in the appendix; and to my colleagues at the Naval Engineering Experiment Station for effective criticism and discussion of the contents, particularly B. F. Treat, A. H. Senner and J. O. White. The material was obtained from a number of tests of rotary pumps for Naval service conducted at the Naval Engineering Experiment Station for the Bureau of Ships.

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Appendix.

Formula for the solubility of air in oils; (Crude, refined oils and other organic liquids).

$$\text{Log}_{10} A = \frac{792}{t+460} - 4 \text{ Log}_{10} \text{S.G.} - 0.4$$

A = air, cubic inch per gallon.

t = Fahrenheit temperature.

S.G. = specific gravity at 60/60 F.

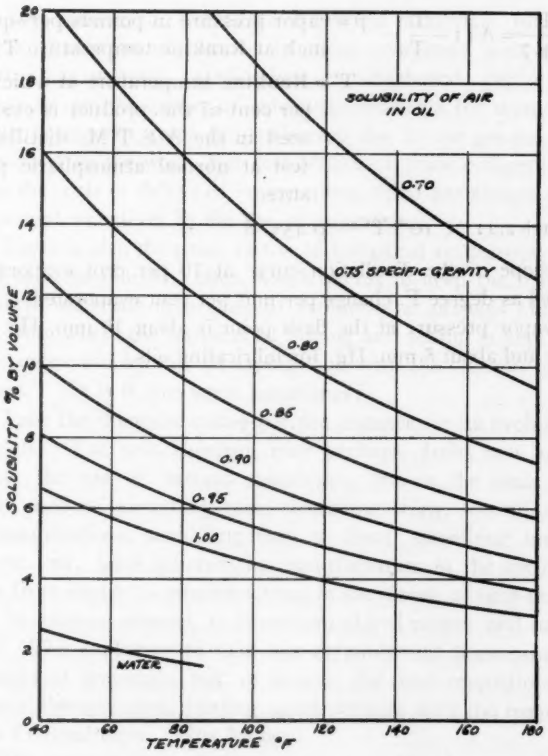


FIGURE 18. SOLUBILITY OF AIR IN OIL AND WATER.

This formula was developed by Dr. C. S. Cragoe of the National Bureau of Standards based on data published up to 1930. This formula has never been published and no particular accuracy is claimed for it, but it does give results which are in fair agreement with the data from which it was derived. This formula is plotted in Figure 18 with the solubility of air in water added for comparison.

Formula for the vapor pressure of oils, (3, 4, 5).

$$\text{Log}_{10}\frac{P}{14.7} = A\left(1 - \frac{T'}{T}\right)$$

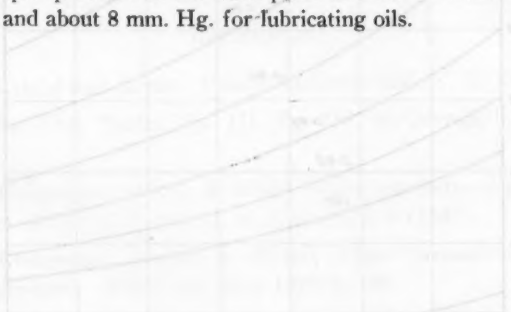
p = vapor pressure in pounds per square inch at Rankine temperature T.

T' = Rankine temperature at which 10 per cent of the product is evaporated in the A.S.T.M. distillation test at normal atmospheric pressure.

$$A = 3.41 + 2.11 \times 10^{-3}\, T' - 0.45\sqrt{S}$$

S is slope of the distillation curve at 10 per cent evaporated, expressed as degree F. change per unit per cent evaporated.

The vapor pressure at the flash point is about 10 mm. Hg. for gasoline and about 8 mm. Hg. for lubricating oils.



SUBSTITUTE ELECTRICAL MATERIALS FOR NAVAL SERVICE.

By C. Huey, Civil Member.*

1. The subject of Substitute Electrical Materials for Naval Service, should be of interest to those concerned with the approval, procurement, application or shipboard performance. Strange to say, the matter of substitute materials for many items, did not necessarily come into existence due to the present shortages caused by the war. But, for reason of trade competition, or due to the costs or delays of importations, there has always existed commercial incentives in the use of substitutes.

2. There is also the great factor of industrial restlessness which exists in these United States, which serves to keep the matter of substitute materials in a state of evolution or perhaps only in a cyclic state where the business of buying and selling is kept seething as expressed by the old saying "off with the old and on with the new." Or is it vice versa sometimes?

3. Take the domestic coffee-pot for instance, in its evolution of materials. The war shortage may perhaps, from now on, accelerate the use of various substitutes, but in the main, other aspects such as, something new, something shiny, something free of contaminations, something easy to clean, something unbreakable, etc., etc., have spurred the manufacturers in the cyclic evolution from copper to enameled iron, to aluminum, to heat-resisting glass, to vitreous enamel, to chromium-plated copper and back, to what? The evolution to date has certainly not been caused by shortages of materials, but, of course, the war restrictions now will turn the evolution, starting again perhaps with the copper pot of the Colonial days. Who knows?

4. The present day substitutes for many Naval materials have the same trend, stimulated by war restrictions and shortages. But

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in general, the process of evolution for many years past has been analogous to the coffee-pot. We can at this point bring to record one of the most debatable substitute materials in its day—rubber in 1916, and again in 1942.

5. In 1916 and earlier there was a hue and cry for the substitution of plantation or cultivated rubber for what was known and still is known as wild rubber, or rubber extracted from the virgin trees in the forests of Brazil and other South American countries. All Navy insulated electric cables required at that time, an insulating wall of vulcanized wild rubber, also known as Up-river Heavea or Para. The stable qualities of the wild rubber had never been questioned, but the commercial pressure for the substitution of cultivated or plantation rubber was carried on for many years, accompanied by many tests and reports showing in general, poorer aging qualities and lower electrical characteristics for the cultivated rubber.

6. However, as time passed, the cultivated rubber trees were set out in favorable climates of the East Indies, were selected, cross-breeded and with maturity, the quality of the rubber obtained has apparently been equal to the wild rubber of South America. The writer has seen no data to bear this out, but all Navy specifications in recent years covering rubber products no longer restrict crude rubber to wild or Up-river Para, but in the main, the restriction is only against re-claimed rubber. Rubber wherever obtained is now required to be "new" rubber with certain minimum tensile strength, elongation, permanent set and aging requirements. In this picture, it is also to be noted that the enormous present day commercial demands for rubber amounting to hundreds of times more than could be obtained in wild rubber, has forced the issue to plantation rubber regardless of equal or inferior quality of the latter. The evolution, of course, is now back to wild rubber due to the seizure by the Japanese of practically all the important rubber plantations, excluding a few experimental plantations conceived by Harvey Firestone and Henry Ford in Africa and Brazil.

7. The history and research on natural rubber, which is processed from the latex or sap of the rubber trees, is very voluminous. But here again, regardless of the laborious technical build-up, and

the enormous investment in processing machinery, the commercial pressure to offer a substitute in the form of "artificial" rubber, dates back well before there were any indications of a shortage or even a predicted shortage of natural rubber. The original incentive here was not due to any demand from the consumer for a substitute, but there has resulted from the work of the chemists and research engineers under the whip of the industrial magnates, a whole series of artificial rubbers, the base of most of which is petroleum. The incentive, prior to the present war shortage, was no doubt initiated some years ago when the price of natural rubber under foreign monopolistic control, rose to an exorbitant figure. After the eventual return to normal, the incentive still continued due to the usual commercial pressure for new products to exploit. As it so happens, artificial rubber becomes a real necessity and the demand for this substitute, for a change, now comes from the consumer and not from the pressure of the industry.

8. In discussing the merits of the prevailing substitutes for Naval Service, no attempt will be made to give technical data to indicate the superiority or inferiority of the substitute as it would obviously be beyond the scope of this article unless each item were to be dealt with separately. It is intended to cover as many items of general interest as time and space permit. Due to the great increase in the Engineering Staff required for the expanded Navy, many of whom are new to their assignments, and not forgetting the "old-timers," the writer has always felt that the service men have not been kept sufficiently informed of developments which evolve from laboratory experiments, industrial research or in the use of substitutes based on scarcity, manufacturing reasons, or technical improvements. Navy purchase specifications are readily available for any one in the Service who is interested in the description or minimum requirements of all materials used on shipboard. But what should we say about the handful of Material Engineers, some of whom are no longer young, who have grown up with the evolutions and substitutions, but have no ready official outlet to inform the Service men of the reasons or necessity for gradual or abrupt changes in materials which appear in Service from time to time. We can readily picture the confusion in the case of Insulated Electric Cables. The service requirements for

the insulating material we might well say have always been the same—moderate electrical resistance, water-proofness, flame-resistance, heat-resistance and aging resistance sufficient for the estimated life of the ship.

9. We first offered a rubber-walled insulated power cable, with an impregnated cotton outer covering. We then without explanation substituted several layers of varnished cambric tape for the inner rubber and a cotton reinforced rubber jacket for the outer covering. The evolution then became a layer of impregnated asbestos felting over the varnished cambric and an outer jacket of impregnated asbestos felting. We may have at this point added aluminum basket-weave armor as a protection to the cable. The present evolution consists of substituting a synthetic resinous compound for the asbestos felting and the substitution of steel armoring for the aluminum. Other substitutions are in the making, such as in the use of glass fibers as a replacement for the asbestos.

10. It would be difficult, if not impossible, for the Service men to dig up the background of the changes and substitutions in the one item of cable alone. Test reports and official correspondence become buried in a few years or else the background of the substitution lies hidden behind the competitive offerings which in time become a recognized requirement. It is therefore high time that the "handful" of Material Engineers start recording the background of the many substitute materials, so that the Service man may know something of the purpose and have a better understanding of what they may expect in the way of performance in the light of the present day offerings. Most all of the materials which will be referred to are to be found on ships still on the active list. The writer, who has drifted (and sometimes rowed) for many years along with many of the substitute materials, will attempt to give the general merits, the advantages or disadvantages and indicate where possible, whether the item is a technical improvement, a substitution due to war scarcity or a commercial substitution based on price considerations or manufacturing economy.

11. As the technical reasons for the use of substitute materials vary greatly with the application to specific Navy items, the discussions will be set forth under classifications to which they have been primarily applied. The generalities or fundamentals, how-

ever, may be applied to other items in the light of the knowledge so obtained, if applicable. The writer has selected three subject items due to their general interest, their wide application and because collectively they invite discussion of most of the basic materials which have already resulted in substitutes or where substitutes may be considered for reasons of conservation of materials. These items are:

(1.) Electric Wire and Cables.
(2.) Searchlight Mirrors.
(3.) Electrical Contacts.

Electric Wire and Cables.

12. Asbestos. *Asbestos* as a substitute for *natural rubber* came about due to the lack of aging properties of rubber and its short life under elevated temperature experienced in boiler-rooms or in the Tropics. While in its resilient stage, rubber still has predominating advantages over asbestos in its electrical characteristics and water proofness under rigorous bending, twisting and stretching conditions experienced in installation or operation. Rubber is suitable for the coldest temperature experienced in Naval Service and when specially compounded and cured in pressure molds, its resistance to abrasion such as required for portable cables, is of the highest order.

13. The lack of heat-resistance and aging properties, especially for permanent installations, permitted the consideration of asbestos as a substitute. The added feature of the fire-resistance of asbestos compared with highly combustible rubber was not overlooked. In the use of asbestos, which was machine felted as a tube over the conductor and impregnated with waxes for homogeneity and water-resistance, we gained heat resistance and aging properties but lost out on water-proofness and insulation resistance. These latter two essential properties were partly recovered by the additional application of five to seven wrappings of lubricated, varnished-cambric tape. However, the fire-resistance property of pure asbestos was never fully realized, due to the presence of about 15 per cent of cotton fibers necessary for manufacturing reasons, the use of waxy or asphaltic impregnants, and finally the

addition of inflammable varnished cambric. In the case of a compartment fire, however, the effect of the burning-out of all the inflammable materials, showed in several happenings, that the remaining asbestos matrix would serve for emergency operation. In order to restrain the propagation of the flame along a burning cable, chlorinated waxes for impregnants were introduced. This class of waxes although still inflammable, evolve a fire-extinguishing gas when burning, which in time becomes self-extinguishing.

14. The failure of asbestos as a waterproof or water-resistant substitute for rubber, even when impregnated by any known method or materials, has recently resulted in the addition of a new substitute material known by the general term of "*Synthetic Resins.*" These *resins* are formulated entirely from inexpensive domestic products. The processing is somewhat costly and requires special skill and considerable technical knowledge at the factories to produce resin which when finally processed by the cable manufacturers, will have the desired physical characteristics. In general, the characteristics are, flexibility, high tensile strength with some recovery after stretching, black, reddish-brown or semi-transparent, depending on the factory formula, and an appearance or feel similar to a combination of rubber and leather.

15. On single and multiple-conductor power cables, the synthetic resin is used as an outer waterproof jacket and may be extruded-on in a hot plastic state without the use of asbestos or maybe fabricated first as a tape with a coarsely woven asbestos tape as a matrix, the jacket then being formed to the required thickness by several layers butted and overlapped between. In the latter method, the synthetic resin is heat-cured so as to result in sealing the butt joints and bonding the layers.

16. Synthetic Resins. *Synthetic Resins* as a substitute for *Asbestos,* has resulted in obtaining a waterproof jacket of enduring life without deterioration, at most ambient operating temperatures. High electrical insulation has also accompanied the use of these materials, although not entirely essential as they are used primarily as mechanical jackets. Single conductors or multiple conductors of power cables, are at present electrically insulated by varnished cambric and felted asbestos as formerly used with asbestos jackets.

17. Synthetic resins have an additional virtue in that, although not fireproof, they have self fire-extinguishing properties resulting from emitted flame-extinguishing gases. On the other hand, due to the characteristics of the material, we have a definite cold temperature limitation of approximately 32 degrees F. where the material becomes stiff or fragile. In this condition it ruptures when bent or twisted. When installing cables, this limitation must be recognized. There is likewise a high limiting temperature of approximately 195 degrees F. which if exceeded as a result of the ambient temperature plus the heat of the operating load, will cause the synthetic resin to expand and revert back to a plastic stage. The use of a braided metal armoring has been adopted to restrain this tendency and which permits successful performance at the 195 degree F. limiting temperature.

18. Summarizing the pros and cons of synthetic resins, we have for the pros, a domestic material and several large sources of supply, a non-aging material, waterproofness as a material, unaffected by acid or oils, good electrical resistance and self fire-extinguishing properties. For the cons, we have a material with definite low and high limiting temperature, some manufacturing difficulties in obtaining complete waterproof fabrication both in the extruded and taped processes, the additional requirement of metal armor to restrain the plastic flow tendency, the somewhat lack of standardization or control of the chemical formula and processing, and at present, a manufacturing shortage due to the large shipbuilding program.

19. ARTIFICIAL RUBBER. *Artificial rubber* as a substitute for *natural rubber,* has made its place for all classes of insulated wires used as portable cords or where the cable is required to be rotated or flexed, as in feeders to the turret columns. This substitution was not based on the war shortage of natural rubber, but for the technical reason that artificial rubber of the petroleum base used, is highly resistant to fuel oil, the protection from which in its proximity to possible oil flooding is a necessary requirement on oil-burning ships. Artificial rubber, although somewhat lower in electrical properties than natural rubber, is considered satisfactory for the voltages applied. The aging, heat, cold, and abrasion resistance properties of artificial rubber, are in general somewhat similar to natural rubber.

20. Due to the fact that artificial rubber is a formulated material and is more or less in a state of evolution, the exact comparison with natural rubber is subject to revision. However, the outstanding features, that of oil resistance and the domestic source of supply, classes it as a practical substitute for natural rubber where stability and flexibility is required at temperatures from 10 degrees F. to 195 degrees F. Flexible cables for special purposes have been recently used consisting of an inner thin layer of *natural rubber* for conservation, plus higher electrical properties, and an outer thin layer of *artificial rubber* for conservation and its oil resistance properties. The desirable bonding between these greatly different materials was found to be satisfactory and its further application is warranted.

21. Glass Fibers. *Glass fibers* as a substitute for *asbestos* has recently been accepted from manufacturers where it is of their own choosing. In the choice of glass fibers, which is readily woven into tape form similar to asbestos to which waterproofing synthetic resins may be applied as a taped jacket, the consideration has probably been based on commercial reasons of there being a large domestic supply as contrasted with asbestos which is imported and high in cost for the type used. The mechanical and electrical characteristics of glass and asbestos are greatly similar. Both materials are highly stable under extreme temperatures, have indefinite aging properties, are resistant to oils and acids, and are flame-proof if considered without impregnants. Both materials have limiting features if exposed to a high temperature fire. The glass fiber melts and reduces to a few drops of glass whereas the asbestos reduces to a fragile powdery ash.

22. Synthetic Resins. *Synthetic resins* as substitutes for *Insulating Enamel* as formerly used on communication cables as the prime electrical insulation have recently been adopted. The use of the latter, although generally satisfactory when further protected by woven coverings of silk or cotton, defects in the enamel did not furnish entire reliability as to waterproofness between the multiple conductors. The substitution of synthetic resin plus coverings of impregnated woven glass fibers, cotton or asbestos, has resulted in a satisfactory electrical and mechanical construction for multiple-conductor communication cable and switchboard wiring.

23. Artificial Silk. *Artificial Silk* (*Rayon*) as a substitution for *natural silk* has been adopted as of to-day, due to war failure of the silk market. But on the other hand, the commercial pressure for the substitution of domestic artificial silk was well under way prior to any visible shortage of imported silk. These materials are used as separators on multiple conductor cables and are combined in various colors to form a color code to identify the individual conductors. Cotton has also been used for the same purpose but the superiority of artificial silk or natural silk is based on better aging properties and fastness of applied colors. Technically there appears to be no choice in the use of artificial silk over natural silk as used on cables, although for many other applications natural silk would no doubt be preferred due to some undefinable property that nature has provided as it has done also in the case of natural rubber.

24. Steel Armor. *Steel armor* as a substitute for *Aluminum Armor* has come into effect as a war measure and the resultant conservation of aluminum. Armor in the form of a basket weave has been used on all types of permanently installed cables for some years past and was adopted after the abandonment of metal conduit and lead jackets. The use of the basket-weave armor on the older re-inforced rubber-jacketed cables and the asbestos-jacketed cables has been for reasons more or less in dispute. The armor is said to have served to prevent abrasion of the fabric jackets during installation. The jackets, however, withstand abrasion better than the armoring. The use of the armoring for protection against rodents, was suggested. The use of the armor as a good under-surface for the application of decorative paints is mentioned. The fire-retarding property of the armoring during an external fire is probably a valid reason for the use of the metal armoring on the older type cables.

25. With the recent advent of the synthetic resin-jacketed cables, the use of the armoring has become a necessity. As previously indicated, the plasticity of the resins at the high temperatures which may be experienced due to overloads or adjacent fires, requires the restraining basket-weave armor. A complete 100 per cent coverage would be the ideal restraint, but the highest practical coverage is limited to about 95 per cent. This leaves 5 per

cent interstices through which oozing of the resins may be experienced under extreme high temperature conditions.

26. Aluminum wire had been used in recent years on account of the saving in weight during the period of weight limitation on all warship construction. At present, due to definite restrictions in the use of aluminum except where no substitute can be offered, steel basket-weave armor has now been adopted as a substitute. As the weight factor on warships is still a consideration, it has been found necessary to reduce the percentage coverage of the steel armor from 95 to 70 and by selection of a smaller gauge wire, any increase in weight of the cable has been avoided by this substitution. This, of course, is at the sacrifice of the main purpose of the armoring and is distinctly a war measure.

27. LEAD ALLOY. *Lead Alloy* as a substitute for *Tin* is being authorized as a coating on the individual copper wires of all Navy cables as a war conservation measure. Tin, for many years, had been used for two technical reasons, first, as a protective coating to prevent the serious deterioration of the individual copper wires from free sulphur which exists in all vulcanized rubber. However, since the substitution of non-rubber materials as the insulation for the conductors, the practice of using tin coating, was continued as a desirable practice. Copper oxidizes very readily in the presence of salt water or air which may be entrapped or absorbed by the cable by a breathing action when heated and cooled. No particular deterioration effects are expected from the chemical action of any of the materials used as substitutes for rubber.

28. The second technical reason for the use of tin, has been to have available a non-oxydized surface on the copper wires at the cut ends of the cable at which point attachment lugs are applied of the soldered, or solderless clamp types. Tin, in its commercially pure form, is readily applied in factory production. Its reasonable cost in the amounts used as a coating, together with its shiny presentable surface when exposed to view, its softness and its inertness to the many elements which readily tarnish copper, rates tin as the first choice of a metal coating for copper wires.

29. The use of a lead alloy as a substitute for tin in Naval Service, is based entirely on the conservation of tin. However, lead alloys have been consistently used in commercial practice for many

years in technical competition with tin. The advantages claimed for the lead alloy are, its lower cost, protection from the same corrosive agencies as claimed for tin, and additional protection from some of the stronger agencies experienced in some commercial installations. The lead itself oxidizes readily, usually as a light surface coating which mars its appearance and requires removal for a good electrical contact.

Searchlight Mirrors.

30. Metal Mirrors. *Metal Mirrors* as a substitute for *Silvered Glass Mirrors* as used on searchlights, have been the subject of considerable technical controversy over a period of time dating from 1916 to the present. There should have been a much quicker change from glass to metal on the basis of the fragility factor alone. Glass mirrors in searchlight sizes of 12 inch, 18 inch, 24 inch, and 36 inch, held the technical leadership far beyond their time. This was probably based on faster working of the glass in production, the ease of obtaining high degree of focal accuracy, the high efficiency of glass and silver, the long life of the glass and silver if mishap or abuse has been avoided.

31. However, it was obvious since the advent of the machine gun and the demolition bombs, that silvered glass mirrors, regardless of their many advantages including the proper spectrum characteristics, would be replaced by a metal substitute as soon as the proper material could be formulated and be produced in form suitable for grinding and polishing by a competent optical factory. It just so happens that all the Navy searchlight mirrors over 12 inches diameter have been produced by one American concern. The change from glass to metal involved the scrapping of a long established glass mirror business, re-tooling, and considerable experimental work at the factory before the substitution was considered to be optically comparable with silvered glass.

32. When speaking of metal mirrors for Naval Service, it simplifies the recording to mention only one of the earlier offerings which proved to be immediately successful. This is identified under the trade name of "*Stellite*," formulated from nickel, chromium and cobalt. *Stellite* has a very hard tenaceous surface and polishes to a long-life, high lustre, with spectrum characteristics

suitable for searchlights. It is very highly resistant to salt water corrosion and to atmospheric or carbon-arc gasses. The use of the *Stellite* metal mirrors as a substitute for glass, has been on a technical basis only and at a considerable increase in price. We have replaced the fragile glass with an extremely tough, solid, one piece metal, capable of being highly polished and which polish can be readily maintained in service by ordinary cleaning. It can be reground and re-polished by the factory, if required after a severe mishap.

33. The war scarcity of the materials used in the Stellite mirrors has recently brought out numerous metal substitutes. These substitutes can be divided into two general classes. *First,* those in which a suitable expensive metal is plated-on an inexpensive formed matrix. *Second,* those formed from solid materials, ground to optical requirements and polished. Most of the present-day offerings which are appearing on the basis of war substitutes, have appeared in past years from time to time on the basis of being technical substitutes, with the exception of a certain brand of a " stainless " steel mirror identified in the trade name as " Hastaloy," there appears to be no other promising substitute for Stellite at present, although there is some activity in the development laboratories. Stellite mirrors as of to-day, are considered to be the best selection from a technical standpoint. Any substitution during the present period will be influenced by cost, deliveries, or shortage of skilled labor and material.

Electrical Contacts.

34. Substitute materials for *electrical contacts* opens up an unsatisfactory subject which dates from the earliest years of applied electricity and is still with us as a problem. We will narrow the subject by not referring to fixed or permanent contacts which may be bolted, clamped or brazed. With contacts operated manually, mechanically, or electrically, many problems of material substitutes have arisen over the entire years of application. Selection of the material for some particular design problem, has always been mostly by " trial and error " influenced by cost, except in the most expensive units, where designers have been known to have used of their own free will, *platinum,* the most expensive. It has

not been the practice of the Navy to specify the material of the contacts. Performance has been the criterion of acceptance which in so far as pertains to contacts, has always been more or less vague and unsatisfactory.

35. Yes, dear reader, you see why we opened up this section on Electrical Contacts using the expression "unsatisfactory subject." We are at a loss to know how to build up the Material Substitute background of electrical contacts based either on technical improvements or on war shortages of materials unless we add the items—lack of technical knowledge and experience in the choice of the most appropriate material for the intended application, and, the continued tendency to save in cost of the contacts, either by choosing a cheaper material of short life or by choosing a suitable higher cost material but skimped in the amount of material used. Let us examine into the background of contacts used since the earlier years, on vibrating bells and horns, telegraph keys, relays, limit switches, push button starters, searchlight mechanisms, gasoline engine distributors, motor controller, rheostats, circuit-breakers, etc.

36. We will first list the different materials we may expect to find *to-day* in the contacts of the random items mentioned above. With this line of attack, we are immediately forced to list practically every kind of contact material used since the *earliest* days. We might just as well then, list these in order of their technical importance as visualized by the writer, starting in order of merit but ignoring many commercial alloys and mechanical mixtures of several elements which have appeared from time to time:—

Platinum.
Pure silver (99.9 per cent).
Coin silver (70 per cent silver—30 per cent copper).
Tungsten.
Carbon.
Phosphor bronze (copper—tin—phosphorus).
Copper.
Brass (copper—zinc).
Bronze (copper—tin).

37. In looking over the above materials on the basis of shortages or restrictions caused by the War, it would appear that the

squeeze, if any, falls on the highest rated material—*platinum.* In this connection, platinum unalloyed makes an excellent contact material, but the addition of a small percentage of iridium (5 to 10 per cent), serves to harden it for better mechanical resistance to wear. Platinum, however, is frequently used unalloyed as the dividing line where iridium should be used, appears to be not well defined.

38. PLATINUM. *Platinum* (or its alloy) as a contact material, has been the first choice for many years where cost has been seriously weighed against reliability. The cost of platinum (and iridium) has always been greater than gold and it is obtained chiefly from Russia. Regardless of the high cost and probable difficulty of obtaining it, no suitable substitute has been offered and its use has been found to be a positive necessity in many of the complicated control or communication circuits in the navy, especially where low current and fractional voltages are distributed through miniature switches and relays. The virtues of platinum are, its very high melting point and its consequent resistance to arc burning, inertness to all service corrosive gases or liquids, high sustained resistance to oxidation and suitable electrical conductivity.

39. The foregoing indicates that we have no present substitute for the best of the contact materials. Its use therefore is predicated on cost and the necessity of the utmost reliability regardless of cost. If platinum ever happens to be as cheap as copper, its universal application to practically all contacts would be in order. However, in looking over the list of the many electrical devices with non-critical circuits, or non-important applications, the *cost* of the material selected is usually given first consideration. Here we may group brass, copper, phosphor-bronze and carbon in the lowest class. Where performance has been unsatisfactory due to excessive oxidation or high contact resistance, designers have selected silver or tungsten as a substitute. These materials may be called class two as to cost. In connection with the use of *silver,* there was a period a short time ago when *coin silver* (70 per cent silver—30 per cent copper) due to its ready availability, was being offered as an improved substitute in non-critical circuits or devices. Experience showed, however, that the presence of even a small amount of copper had all the objectionable characteristics of plain

copper in its ready oxidation and consequent high contact resistance.

40. PURE SILVER. *Pure Silver,* therefore, has definitely obtained a place as a fairly good substitute for platinum. Its cost in the amounts generally required is reasonable and it is available without importation. The virtues of pure silver are, its high electrical conductivity and its sustained low contact resistance even if showing discoloration from arcing or oxidation. It has not the high melting point of platinum and therefore its comparative resistance to arcing would be indicated on the basis of its relatively higher erosion factor but not necessarily by any impairment in its contact resistance. From the foregoing it is indicated that silver may be substituted for platinum even in critical circuits where arcing is negligible. However, the proof of the neglibility should be based on test or service.

41. TUNGSTEN. The use of *tungsten* as a contact material appears to be limited principally to the breaker points in gasoline engines distributors, in the low voltage side of the ignition circuit. The virtues of tungsten in this application are, its resistance to severe mechanical wear, its reasonable resistance to erosion from the arcing experience, its satisfactory resistance to oxidation and its reasonable cost. Due to the well-established commercial adaptation of tungsten for this purpose and its generally satisfactory performance, any substitution would be difficult to conceive of at present. However, in the breaker point of magnetos, where longer and more reliable service would be in keeping with the cost of the unit, platinum-iridium contacts are to be expected.

42. CARBON. *Carbon* as a contact material holds a peculiar place in its application to electrical circuits. It is inherently a high-resistance material both as to contact and structurally. Its outstanding virtue is its ability to withstand severe arcing without oxidation of its surface. No substitute material for carbon has been found where severe arc-rupturing is experienced such as on circuit-breakers which operate in air or where an inherent resistance material is required such as for commutator brushes of motors and generators.

43. Due to the fragility of carbon in general, and its physical limitations in withstanding the explosive or rupturing forces ex-

perienced in air circuit-breakers of the higher rated volts and amperes, inventors instead of finding a substitute material for carbon, have succeeded in applying arc-suppressor devices in the form of magnetic blow-out coils, de-ionizing metal chutes, or enclosing pressure-chambers, any of which serve to satisfactorily suppress the arc within their ratings, without the use of carbon.

44. Carbon has been used to some extent as a sliding contact for variable-resistance rheostats and similar adaptations. Its chief virtue in these applications, is in its non-abrasive property without the necessity of using lubricants. However, due to its undesirable and varying contact resistance, brass, copper or silver has been found to be a suitable substitute, if provisions are made for occasional lubrication of the sliding contact surface to prevent scoring or excessive wear. Brass against copper or, silver against silver, make good wearing surfaces.

45. PHOSPHOR-BRONZE. *Phosphor-Bronze* (copper — tin — phosphorus), is a material which has been used for many years in flat strips or formed shapes, mainly in applications where a spring effect is required as part of the design. It has fair electrical conductivity but its use is justified only for its resistance to corrosion under installation conditions. Fuse clips up to 60 ampere sizes are usually made of phosphor-bronze. In general, phosphor-bronze, is somewhat unreliable from a mechanical standpoint. Commercially it varies greatly and usually it cannot be safely overstressed. In general, other non-corrodible spring metals may be substituted if sufficient conductivity is contained in the metal for the application, such as spring brass or copper.

46. COPPER. The use of *copper* for contact material has probably been the starting point in the design of all the earlier and the earliest electrical devices. The common knowledge of the very high electrical conductivity of copper, the inexpensiveness of the metal, its workability, and the attractive surface finish which can be applied and sustained with lacquer, still ranks copper as the number one metal in the industry. The large quantities of copper in service, of course, is not based in its application to arcing contacts or other forms of contacts discussed herein, but to such items as knife or lever switches, the main contacts of circuit-breaker, commutator bars and many other applications transmitting the smallest to the largest power ratings.

47. In the application of copper to electrical devices, the two objectionable characteristics of copper should be avoided in the design and application. The first, is its ability to take on an oxidizing, insulating film, almost immediately after it is cleaned by filing, sanding or grinding. This film can be greatly retarded to a practical extent, such as on lever or knife switches, by the immediate application of a film of oil or grease. Where switches operate under oil for the suppression of the arcing, this problem is, of course, not encountered. The second, is the insulating spots or burnt areas developed by relatively small amounts of arcing. This condition on circuit-breakers is reduced by the use of auxiliary contacts either of readily renewable copper or carbon or both. On lever or knife switches operating in air, the infrequent use or the reduction in the current load before opening the circuit, is the main dependency for long life without recourse to filing or dressing the arcing edges of the copper. In every case in the design of the apparatus using copper as the contact area, should incorporate a sliding or wiping action of sufficient pressure to result in removing the insulating film. If otherwise, the electrical power losses at the contacts become progressively higher with consequent increasing heat and further increase in the insulating areas.

48. Regardless of the objectionable characteristics of copper as a contact material, it has well served the industry. Copper unfortunately is one of the metals to be conserved due to the great demand for war purposes other than in the electrical industry. The substitute for copper, if cost can be disregarded, is silver. Silver is not only a substitute but it is an excellent substitute for many applications where copper is now firmly entrenched. There is said to be millions of ounces of silver held in reserve by the Government. The cost of silver per ounce, is far greater than the cost of copper is per pound. However, if necessity outweighs cost, the use of the substitute is obvious.

49. Brass. The application of *brass* as a contact material is rather extensive when we consider its employment in the vast number of incandescent lamp-bases, lamp-sockets, pronged plug-ins, snap switches, etc., etc., used in Naval Service. Brass is an alloy of copper and zinc and may be described as bright yellow in color, hard, ductile and malleable. The proportion of copper to

zinc is usually left to the manufacturer. A good grade of brass will run around 66⅔ per cent copper—33⅓ per cent zinc. Malleability starts around 55 per cent copper—45 per cent zinc at which point production machines dictate the actual proportions of the two metals.

50. From an electrical standpoint, brass might very properly be called *de-based* copper. The use of the alloy is chiefly for manufacturing reasons. However, the much lower electrical conductivity of brass compared with copper, is off-set in the various applications, by the great increase in the cross-sections and contact areas which are necessary to provide rigidity and operational strength to the current-carrying parts. Brass oxidizes somewhat slower than copper. However, in many applications to Naval Service, platings of nickel, tin, zinc or cadmium have been employed to reduce the corrosion of the contact areas and surrounding parts. The problem is a continuing one in the search for a cheap non-oxidizing alloy or a satisfactory protective plating for the present alloys.

51. Both the elements used in brass, (copper and zinc) are on the war restricted list. The only practical and suitable substitute for brass, appears to be silver. Here again, cost is the great barrier, but necessity of war demands will require a constant flow of brass to the electrical industry, or its substitute—silver. Iron or steel, if properly plated, might as a last resort, be considered a war substitute.

52. Bronze. The use of *bronze* as a contact material is not as extensive as that of brass, for the reason that the latter is the common purpose metal and the first choice of the manufacturer wherever it will operate or where there is no consumer demand for a higher grade metal. Electrical *bronze* is an alloy of copper, as is brass, but with tin substituted for zinc. The copper content is usually high (70 to 80 per cent) which identifies bronze by its rich, copper color. This alloy which is naturally more expensive, with its appreciable tin content, is widely used chiefly in the cast form, as the only satisfactory metal for contact-fingers of motor controllers and contactor arms of many power equipments. It withstands severe arcing and mechanical abuse and with the system of heavy wiping actions, the contact losses are neglible and seldom if ever require renewal or cleaning.

53. Here again the elements used (copper and tin), are on the war restricted list. A satisfactory substitute for bronze is more difficult to conceive of than in the case of brass in view of the severe duty imposed and the necessity of reliable performance in its application to power equipment. Iron or steel mechanical parts with the use of cast silver at the actual contact surface, would be offered as a last resort substitute.

54. This discussion of *electrical contacts,* indicates the ramification of the subject. It is of great importance to successful Naval Service, that the best selection be made of the metals used for each and every item of equipment, in the original design. Since the use of contacts in one modern fighting Naval vessel number into the thousands, the upkeep and servicing of improper or unsuitable contact materials results in waste of man-power and possible failure of vital equipment at a critical time. As a matter of fact even the non-critical equipment, which serve only as modern conveniences in the operation of the galleys, laundries, lighting and the many domestic items, should be well considered as to the choice of contact materials so as to avoid frequent servicing and loss in the use of the equipments in daily service.

Conclusion.

55. The writer has made an attempt to indicate the trend in the use of various basic electrical materials and has given one man's opinion as to the possible substitutes which may be considered either for technical reasons or for reasons of war restrictions on certain materials, notably, copper, tin, platinum, rubber and silk. Many differences of opinion are to be expected both from the manufacturers and the Navy technicians, as to the most suitable materials which should be used if freely available, or where war restrictions require substitutes. These differences have always existed and they serve probably as incentives to develop new materials, to widen the sources of supply and to stimulate competition. However, watchful control at the factories, rigid laboratory tests, and observation of the effect of shipboard service in various parts of the world under variable climatic conditions, are considered to be of utmost importance in obtaining materials of superiority over those of enemy nations.

NICKEL IN BRONZE.

The Effect of Replacing Tin by Nickel on the Porosity, Mechanical Properties and Corrosion Resistance.

By Alfred H. Hesse* and J. L. Basil.†

Introduction.

It has been shown that intercrystalline shrinkage porosity was considerably reduced when 6 per cent nickel replaced 6 per cent tin in composition G [1]. This was considered to be extremely important in connection with the manufacture of bronze castings which are required to withstand hydrostatic pressure, because it was felt that the number of rejections due to leakage would be reduced. Although nickel bronzes were then used to some extent commercially, not too much was known about their internal soundness, or about their mechanical properties and sea water corrosion resistance, all of which must be considered in the choice of material for many marine applications. Therefore, a systematic investigation was undertaken to determine the effect of replacing various amounts of tin by nickel on these properties of compositions G and M and red brass.

Leakage or the lack of pressure-tightness has been attributed to porosity of which there are two general types, intercrystalline shrinkage and gas. Leakage has also been attributed to such defects as cracks, cold shuts and sand inclusions. Gas and intercrystalline shrinkage porosity are rather difficult to eliminate.

Gas porosity in general may be a result of (1) the precipitation of gases soluble in the liquid state but practically insoluble in the solid state, (2) the entrapment of insoluble mold gases while casting and during solidification, and (3) the reduction of metallic oxides while casting to form carbon monoxide and carbon dioxide

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which may ultimately be entrapped. Gas porosity takes the form of spheres in which the metal in direct contact with the gas remains bright and clean, and is generally scattered throughout the sections or is segregated at the metal surface, or both. Unless convenient channels exist between gas pockets from metal surface to surface or unless there are channels extending from surface to surface on gas free castings, leakage would not be expected when the casting is subjected to hydrostatic pressure.

Intercrystalline shrinkage cavities, generally tetrahedral in shape under the microscope, are located at dendrite interfaces. They are formed even under carefully controlled laboratory conditions when melting and solidifying in vacuo [1] thereby negating the possibility of this type of porosity being due to precipitated or entrapped gases. In view of this fact, one logical explanation for the cause of intercrystalline shrinkage porosity is based on the wide freezing range of copper-tin alloys containing approximately 9 per cent tin. Slow or prolonged freezing generally occurs in sand castings. Thus, with a wide cooling range a considerable depth of metal from the cooling face of the casting will be freezing at the same time and the feeding liquid must traverse a long network of dendrites to fill the cavities. Since the cavities are not formed as a result of precipitated or entrapped gases, only one other possibility exists to which their formation can be attributed, namely contraction.

The amount of intercrystalline shrinkage porosity can be controlled by controlling the rate of solidification, i.e. if the casting temperature is above normal, the contraction during solidification will be greater than if cast at a normal temperature. Tin bronzes produce the fewest intercrystalline shrinkage cavities when they are poured at temperatures as low as it is practicable to insure good mold reproduction and to avoid cold shuts. However, the tin bronze sand castings cannot be produced entirely free from contraction cavities even when the most favorable casting temperatures are employed, which is evidenced by the fact that maximum densities for given compositions are not obtained. (Compare Plates 1 and 2). It may be that the highest density obtainable at normal pouring temperatures is sufficient to produce pressure-tight castings, but it is possible to be relatively certain of

obtaining this density within a limited pouring range only; too low a pouring temperature results in such defects as cold shuts, inclusions and poor mold reproduction while too high a pouring temperature results in many internal cavities. Complicated castings are poured at temperatures which are determined by the thinnest section. The pouring temperature may then be much too high for the heavy sections and an excessive cavity formation will result in the heavy sections. Chilling the heavy section will help, but the pouring temperature of these alloys must be held within narrow limits. When 6 per cent tin is replaced by 6 per cent nickel in composition G, maximum cast density may be obtained over a wide pouring range. Thus, a sensitive casting alloy is converted to a more flexible foundry composition. Two distinct advantages are immediately gained: (1) pouring temperature is no longer critical, and (2) the rate of solidification in castings having both heavy and light sections is also less critical so long as the principles of directional solidification are followed.

Since the replacement of 6 per cent of the tin by nickel in composition G was found to produce an alloy which gave lower porosity over a wide pouring temperature range, a study of its corrosion resistance and that of other nickel bearing bronzes was undertaken. Heats of composition G were made in which 3, 6, 7.5 and 9 per cent of its nominal 9 per cent tin were replaced by the same weight per cent of nickel. The effect of nickel on composition M and red brass also was studied. The effect of pouring temperature on porosity, tensile properties and fluidity was determined as well as the effect of composition on the corrosion resistance to Severn River water.

The many variables encountered in the foundry make results difficult to reproduce. In producing large numbers of castings a certain percentage are always rejected due to porosity, low mechanical properties, cold shuts, poor mold reproduction, leakage, or other defects. Even if the molding practice, melting technique and alloy content are carefully controlled from one heat to another, variations in density and mechanical properties occur. By averaging the results of a number of tests, trends become apparent which are often misleading, particularly in casting studies, unless the standard deviations from the mean are considered.

For example, suppose that it is desired to determine how the porosity of a bronze is affected by variations in pouring temperature. After data from several heats have been accumulated, the variations in density for the different pouring temperatures are averaged arithmetically. An average density-pouring temperature curve may then show that porosity increases very little with increases in pouring temperature, while the standard deviations from the mean densities may be narrow at low pouring temperatures and wide at high pouring temperatures. Thus, the mean density-pouring temperature curve of an alloy may show desirable characteristics although the standard deviations may indicate that the density becomes critical at high pouring temperatures, (e.g. Plate 3, density-pouring temperature curve for G*).

Porosity, Mechanical Properties and Fluidity.

(*a*) *Experimental Procedure*

Melting charges consisted of the highest quality virgin metals, selected Naval Research Laboratory foundry scrap of known composition and a master alloy of copper-nickel for nickel additions. Several heats were made of virgin metals alone while the others were prepared from scrap and virgin metals. The properties of the virgin metals heats were approximately the same as those of the heats made from virgin metals and scrap. General foundry practice was simulated by using charges consisting of virgin metals and selected scrap.

All charges for castings to be used for density, tensile strength and elongation determinations were melted in a 210 pound capacity lift coil type, high frequency induction furnace. Charges for corrosion specimens and fluidity spirals were melted either in the induction furnace or in a 120 pound capacity stationery, crucible type, oil fired furnace depending upon the size of the charge. The oil fired furnace was operated with a slightly oxidizing atmosphere, while no attempt was made to control the atmosphere in the high frequency furnace except by means of the usual charcoal cover. Clay-graphite crucibles were used in both furnaces.

Virgin copper, selected scrap and the copper-nickel master alloy (when required) were melted together. Tin was added to the molten metal (if necessary) and sufficient zinc was added to bal-

ance the composition and compensate for melting losses. The melts were stirred a few minutes before pouring the first mold. The metal was heated to approximately 1300 degrees C. when the crucible was removed from the furnace. After skimming, the metal was poured into three molds at 1250 degrees C. (2282 degrees F.), 1150 degrees C. (2102 degrees F.) and 1050 degrees C. (1922 degrees F.), respectively.

Match plate patterns were used for the molds which were made of Albany green sand (Grade 00) or its equivalent containing from 6 to 8 per cent moisture. The molds were allowed to air dry at least 24 hours before casting. The standard bronze test casting, 10A[3], was used extensively for all compositions so that the tests would be comparable to accepted foundry practice. Because of its rather complicated design, the standard aluminum test casting, 11A[3], was also used for tests on composition G, G-1, and G-2. An asterisk affixed to the composition letter signifies that type 11A test casting was used, e.g. G*, G-1*, G-2*. Since type 10A test casting shows merely the properties of the metal, type 11A test casting was used in addition because it gives properties more representative of those in a complicated casting. In order to avoid possible variations, the same melting, molding and casting techniques were employed for each heat.

The running characteristics of the basic compositions were compared with those of the modified compositions by means of the Naval Research Laboratory fluidity test[2]. The fluidity curves were obtained by plotting spiral lengths in inches versus pouring temperature. Five different pouring temperatures between 1100 degrees C. (2012 degrees F.) and 1300 degrees C. (2372 degrees F.) were selected, and enough different heats (a minimum of four) were run to establish an average curve for each composition. Fluidity spirals were poured when the desired pouring temperatures were reached on cooling.

"As cast" density of both rough tensile specimens from each mold was determined by the conventional displacement of water method and standard 0.505 inch threaded and tensile specimens were used. Maximum density values (Table 1, Plate 1) were determined by X-ray diffraction with a back reflection camera. To insure internal soundness and homogeneity one inch cubes of

TABLE I

X-RAY DENSITY VALUES FOR COMPOSITION "G" AND ITS MODIFICATIONS

SPECIMEN† NUMBER	COMPOSITION, PER CENT					
	Copper	Tin	Nickel	Zinc*	Lead	X-ray Density, gm/cu.cm.
5	87.40	9.51		3.05	.04	8.933
28	87.75	8.20	1.12	2.93		8.926
65	88.30	7.12	1.99	2.59		8.930
41	88.42	5.93	2.97	2.68		8.914
46	88.36	4.94	4.17	2.51	.02	8.907
51	88.66	3.90	4.97	2.45	.03	8.927
36	88.75	2.94	5.98	2.33		8.928
56	89.29	1.58	7.41	2.70		8.922
61	88.93	0.00	8.97	2.10		8.928

* By difference

† Alternately cold compressed and annealed from 1" cubes to 1/4" x 1" x 1" pieces.

X-RAY DIFFRACTION DENSITY DETERMINATIONS

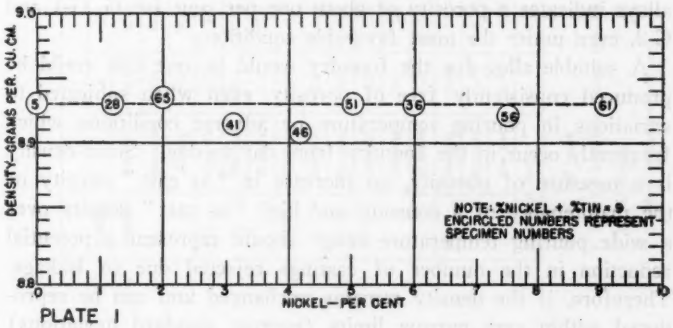


PLATE I

the "as cast" alloys were reduced 75 per cent by several cycles of cold compressing and annealing. These specimens were then trimmed to 1/4 inch by 1 inch by 1 inch coupons, polished and etched before exposure.

Density-, tensile strength-, and elongation-pouring temperature data were obtained by running a number of heats for each composition (Tables II and III). Standard deviations [4] were calculated after the mean values had been computed. The cross-hatched areas in Plates 2, 3, 4 and 5, within which 68 per cent of the observations fall, show the standard deviation from the mean curve which is the heavy line drawn through the center of each area.

(b) Discussion of Results

Since the density of a porous casting is less than the density of a non-porous casting, the degree of porosity may be estimated by a comparison of the densities of the alloy cast under different conditions or with its maximum density. To determine the maximum density of some alloys it is necessary to resort to the procedure employed on the G series, (Table I and Plate 1). The change in maximum density resulting from the replacement of tin by nickel is surprisingly small in view of the difference in density of these elements. A comparison of the maximum densities determined by X-ray methods with the densities of the cast alloys indicates a porosity of about one per cent for G, G-1 and G-2, even under the most favorable conditions.

A suitable alloy for the foundry would be one that could be produced consistently free of porosity, even when subjected to variations in pouring temperature or adverse conditions which frequently occur in the foundry from day to day. Since density is a measure of porosity, an increase in "as cast" density or the maintenance of a constant and high "as cast" density over a wide pouring temperature range should represent a potential reduction in the number of castings rejected due to leakage. Therefore, if the density remains unchanged and can be reproduced within very narrow limits (narrow standard deviations) when subjected to variations in pouring temperature a definite improvement in soundness characteristics has been attained. Plates

TABLE II

CHEMICAL ANALYSIS OF ALLOYS

ELEMENT		CHEMICAL COMPOSITION, PER CENT										
		G	G*	G-1	G-1*	G-2	G-2*	M	M-1	M-2	R.B.	R.B.-1
Copper	Nominal	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	86.0	85.0	85.0
	Maximum	88.9	88.9	88.8	88.4	89.0	88.8	88.2	89.9	86.5	85.4	85.9*
	Minimum	88.0	85.8	87.5	88.0	87.4	88.1	87.7	86.9	85.9	85.2	
Tin	Nominal	9.0	9.0	6.0	6.0	3.0	3.0	6.5	5.5	6.5	5.0	2.5
	Maximum	9.2	10.2	7.1	7.1	3.6	5.0	6.7	6.0	6.5	5.3	2.4*
	Minimum	7.8	7.7	4.3	5.9	2.4	2.9	6.3	4.7	6.1	4.8	
Nickel	Nominal	0.0	0.0	3.0	3.0	6.0	6.0		1.0	2.0		2.5
	Maximum	0.8	1.5	4.0	3.0	6.1	6.0		1.0	2.0		2.3*
	Minimum	0.0	0.0	2.0	2.0	5.6	4.2		1.0	2.0		
Zinc+	Nominal	3.0	3.0	3.0	3.0	3.0	3.0	4.0	4.0	4.0	5.0	5.0
	Maximum	3.0	3.3	4.0	2.8	3.9	2.8	4.2	4.4	4.3	4.7	4.8*
	Minimum	1.9	1.9	2.9	2.5	2.5	2.3	3.8	3.3	3.4	4.5	
Lead	Nominal	0.00	0.00	0.00	0.00	0.00	0.00	1.5	1.5	1.5	5.0	5.0
	Maximum	0.09	0.04	0.06	0.02	0.32	0.02	1.5	1.5	1.8	5.2	4.7*
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	1.3	1.1	1.1	4.9	
Number of Heats		7	8	7	4	6	6	5	7	4	3	1

R.B. - Red Brass

* Type 11A Test Mold; others type 10A Test Mold

+ By difference

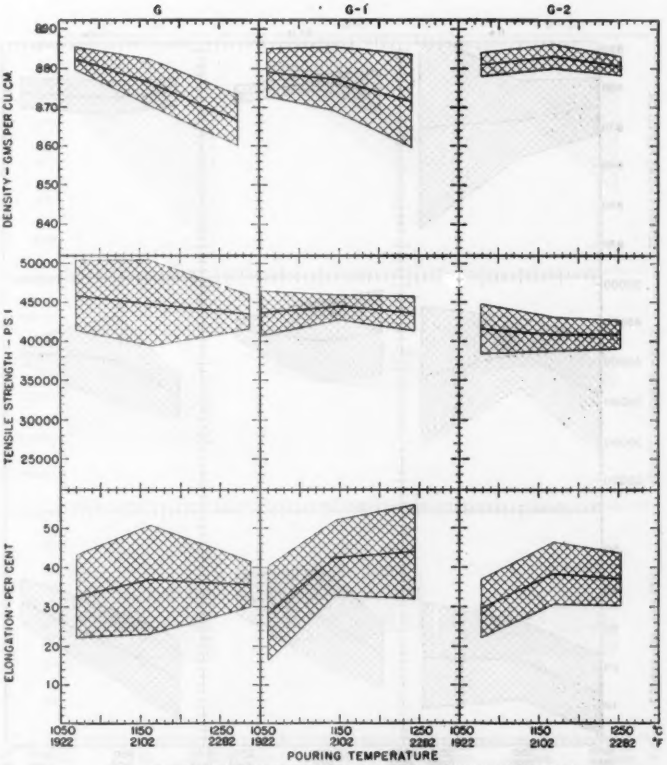
* Chemical analysis of one heat

TABLE XII

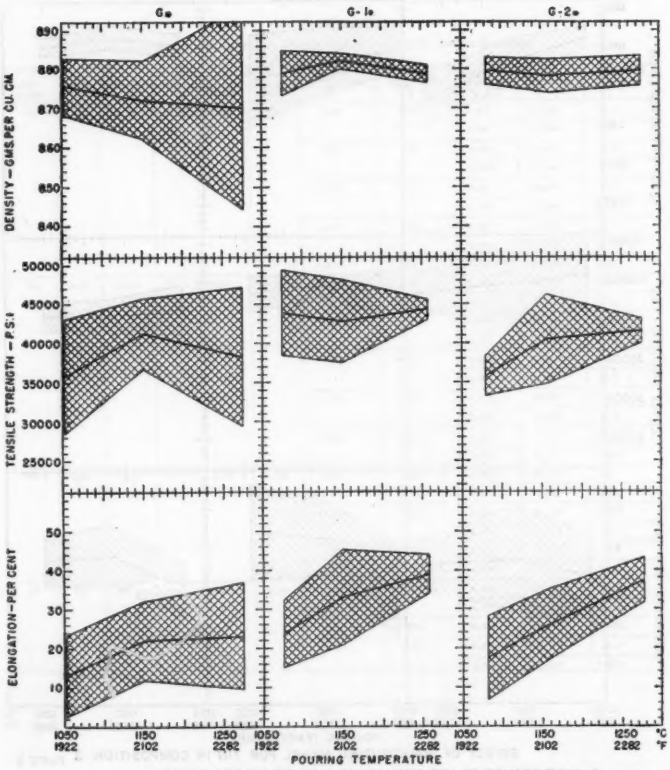
DENSITY, TENSILE STRENGTH AND ELONGATION OF 7.5 AND 9 PER CENT NICKEL BRONZES

HEAT NUMBER	MELD TYPE	COMPOSITION, PER CENT				POURING TEMPERATURE °C	POURING TEMPERATURE °F	DENSITY, gm. per cu. cm.	TENSILE STRENGTH, p.s.i.	ELONGATION per cent.
		Copper	Tin	Nickel	Zinc					
35	11A	88.39	1.58	7.41	2.72	1320	2408	8.839	35,800	28.3
								8.809	37,000	28.1
						1230	2246	8.819	37,500	35.9
								8.837	37,800	35.9
						1180	2156	8.814	38,800	35.9
								8.800	31,100	12.5
						1140	2084	8.861	37,600	38.9
								8.802	37,700	32.9
						1090	1994	8.738	27,100	14.9
36	11A	88.93	0	8.97	2.10	1325	2417	8.866	28,700	28.1
								8.852	29,900	46.1
						1270	2318	8.813	33,300	31.3
								8.828	28,500	18.8
						1225	2237	8.827	27,300	30.3
								8.823	29,500	27.3
						1165	2165	8.873	30,900	30.5
								8.868	32,100	28.9
						1130	2066	8.755	19,800	11.7
								8.843	28,200	14.8
96	10A	89.17	0	8.88	1.95	1280	2336	8.876	29,900	28.1
								8.867	29,300	29.0
						1180	2156	8.931	31,900	43.2
								8.876	28,600	27.3
						1120	2048	8.872	33,100	33.6
								8.897	33,300	48.4
99	10A	88.48	0	9.17	2.39	1260	2300	8.953	28,300	22.7
								8.875	29,900	24.2
						1160	2120	8.869	29,000	26.6
						1090	1994	8.836	33,000	32.8
								8.854	33,000	33.2

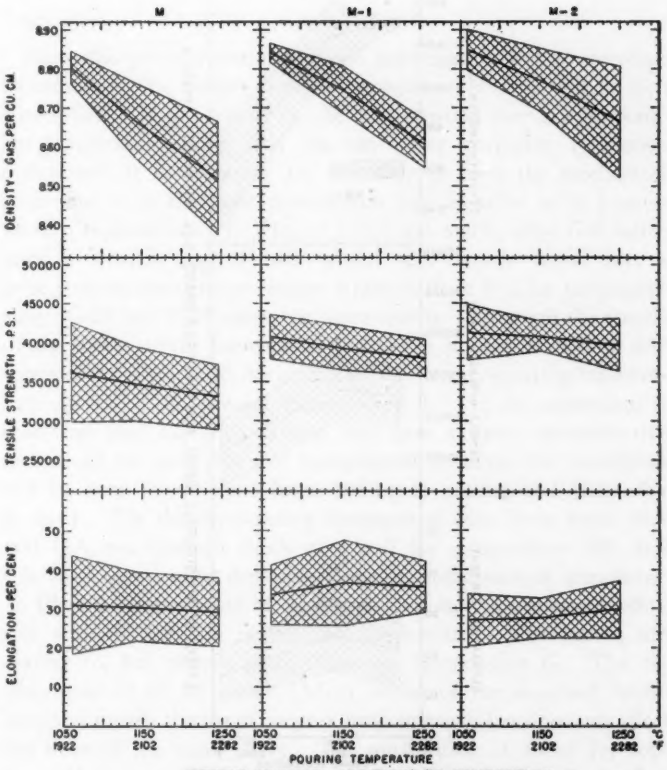
a By difference



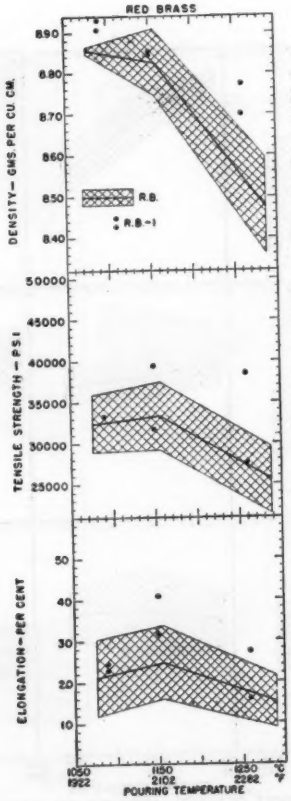
EFFECT OF SUBSTITUTING NICKEL FOR TIN IN COMPOSITION G PLATE 2



EFFECT OF SUBSTITUTING NICKEL FOR TIN IN COMPOSITION G PLATE 3



EFFECT OF NICKEL ADDITIONS TO COMPOSITION M PLATE 4

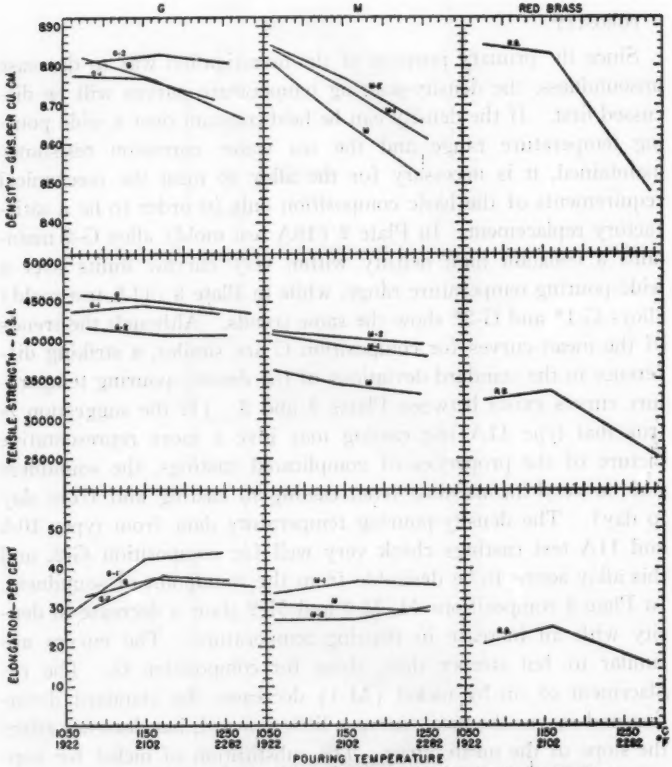


EFFECT OF SUBSTITUTING NICKEL FOR TIN IN RED BRASS (10A TEST MOLD.) PLATE 5

2 and 3 show the effect of replacing tin by nickel in composition G, Plate 4 shows the effect of nickel on composition M, Plate 5 shows the possible influence on red brass, and Plate 6 is a composite of the mean (average) curves for data recorded on Plates 2, 4 and 5.

POROSITY

Since the primary purpose of the investigation was to decrease unsoundness, the density-pouring temperature curves will be discussed first. If the density can be held constant over a wide pouring temperature range and the sea water corrosion resistance maintained, it is necessary for the alloy to meet the mechanical requirements of the basic composition only in order to be a satisfactory replacement. In Plate 2 (10A test mold) alloy G-2 maintains a constant high density within very narrow limits over a wide pouring temperature range, while in Plate 3 (11A test mold) alloys G-1* and G-2* show the same trends. Although the trends of the mean curves for composition G are similar, a striking difference in the standard deviations of the density-pouring temperature curves exists between Plates 2 and 3. (If the suggestion is true that type 11A test casting may give a more representative picture of the properties of complicated castings, the soundness will be very inconsistent from casting to casting and from day to day). The density-pouring temperature data from types 10A and 11A test castings check very well for composition G-2, and this alloy seems to be desirable from the standpoint of soundness. In Plate 4 compositions M, M-1 and M-2 show a decrease in density with an increase in pouring temperature. The curves are similar to, but steeper than, those for composition G. The replacement of tin by nickel (M-1) decreases the standard deviation and moves the mean curve a little upward, but does not affect the slope of the mean curve. The substitution of nickel for copper (M-2) moves the mean curve upward, but does not affect its slope. The standard deviation is about the same as it is for composition M. In Plate 5 even though only three heats were run on red brass the trends are indicated. Only one heat of R.B.-1 was run because the resistance to corrosion of the alloy in Severn River water did not compare favorably with the resistance



MEAN CURVES FOR TIN BRONZES AND THEIR MODIFICATIONS PLATE 6

to corrosion of the basic composition. There is no indication that the replacement of tin by nickel will produce the same results as obtained in the G series, although, it is likely that the mean curve would have moved upward. By comparing the mean density-pouring temperature curves (Plate 6) of the basic composition G and M and red brass, it may be seen that as the lead content increases from 0 per cent in composition G to 5 per cent in red brass, the density which remains constant with variations in pouring temperature for composition G becomes critical to pouring temperature for composition M and red brass.

In Table III the density of the 7.5 per cent and 9 per cent nickel bronzes remained constant when the pouring temperature was varied. However, in view of the poor sea water corrosion resistance and low tensile strength of these alloys, work was discontinued.

MECHANICAL PROPERTIES

Having shown a means by which internal soundness may be improved, the next question is, can the modified compositions meet the minimum mechanical requirements listed below for compositions G, M and red brass.

	Tensile Strength P.S.I.	*Elongation Per Cent in Two Inches*
Composition G	40,000	20
Composition M	34,000	22
Red Brass	30,000	20

In Plate 6 the mean tensile strength- and elongation-pouring temperature curves show that these requirements can be met. Plates 2 and 4 show the standard deviations for compositions G and M and their modifications. In Plate 2 the tensile strength of composition G-2 is a little lower than compositions G and G-1, however the standard deviations for G-1 and G-2 are much smaller than for G. The elongation of composition G-2 is also lower, but again the standard deviation is much smaller than for both G and G-1. Although the progressive replacement of tin by nickel results in less variation in properties, the mechanical

properties of the alloys seem to be lowered somewhat. The mechanical properties of composition M are not lowered when tin is replaced by nickel (Plate 4). The tensile strength of M-1 and M-2 and the elongation of M-2 are very much more stabilized. Plate 5 shows that the mechanical properties of one heat of R.B.-1 were a little higher than the basic composition (R.B) and that the same trends with pouring temperature are probable.

In Plate 3, 11A test mold, a non-standard type for bronze, was used. Pouring temperature has less effect on the mechanical properties than appeared from the smaller amount of data reported earlier [1]. Additional data show that the mechanical properties are less sensitive to pouring temperature, but the average values of 11A test mold data when compared with 10A test mold data are somewhat lower than the minimum requirements particularly at the low temperature end of the pouring range. In spite of the low mechanical properties, the densities of G-1* and G-2* are still satisfactory, while G* shows a very wide standard deviation. Though the mechanical properties fall below the minimum requirements when tested under non-standard conditions, compositions G-1* and G-2* are equal to or superior to composition G*.

FLUIDITY

The replacement of 6 per cent tin by 6 per cent nickel in composition G markedly lowers the fluidity, (Plate 7, curve G-2). Likewise, the replacement of 2.5 per cent tin by 2.5 per cent nickel in red brass lowers the fluidity somewhat, (curve R.B.-1). Other additions or replacements of tin by nickel in bronze have no marked influence on fluidity. It follows that for compositions G-2 and R.B.-1 a pouring temperature higher than normal for the basic compositions is required.

MICROSTRUCTURE

Several pieces of each composition cut from the ends of the tensile bars before pulling, were examined microscopically (Plate 8). All compositions except G-2 showed the typical cored structure with intercrystalline shrinkage cavities at the dendrite interfaces. G-2 showed no evidence of coring and there was a marked lack of intercrystalline shrinkage porosity. This further substantiates its high "as cast" density.

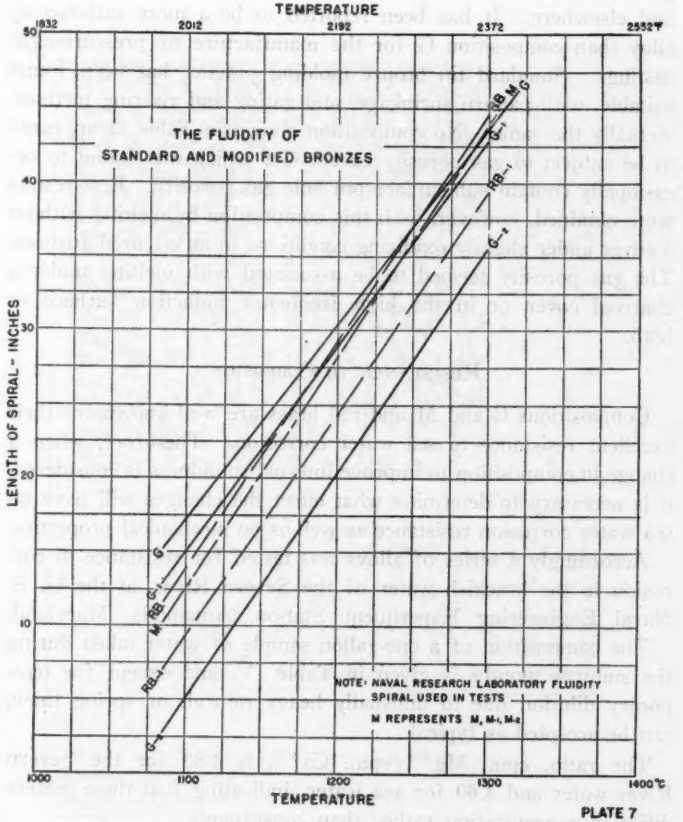

TEMPERATURE
1832
2012
2192
2372
2552°F
THE FLUIDITY OF
STANDARD AND MODIFIED BRONZES
LENGTH OF SPIRAL - INCHES
50
40
30
20
10
G
G-1
HB
M
HB-1
G-2
NOTE: NAVAL RESEARCH LABORATORY FLUIDITY
SPIRAL USED IN TESTS
M REPRESENTS M, M-1, M-2
1000
1100
1200
1300
1400°C
TEMPERATURE

PLATE 7

GENERAL

Complicated castings have been satisfactorily made from composition G-2 in the foundry of the Naval Research Laboratory and elsewhere. It has been reported to be a more satisfactory alloy than composition G for the manufacture of pressure-tight castings. Standard tin bronze molding practice has been found suitable, with pattern shrinkage, and gating and risering methods virtually the same. No composition shown in Table II appeared to be subject to gas porosity except G-2 which was found to occasionally contain sub-surface pin hole gas porosity. Best results were obtained, however, with this composition by melting without a cover under slightly oxidizing conditions in an oil fired furnace. The gas porosity seemed to be associated with melting under a charcoal cover or in the high frequency induction furnace or both.

Resistance to Corrosion.

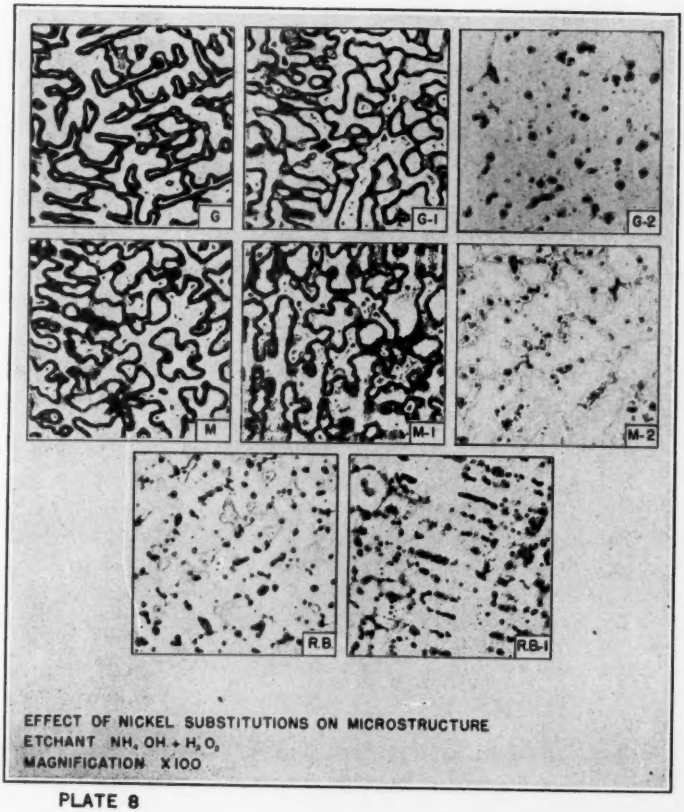
Compositions G and M and red brass are well known for their excellent resistance to sea water corrosion. Therefore, when a change in composition to improve internal soundness is considered, it is necessary to determine what effect the changes will have on sea water corrosion resistance as well as on mechanical properties.

Accordingly a series of alloys was tested for resistance to corrosion in the brackish water of the Severn River, at the U. S. Naval Engineering Experiment Station, Annapolis, Maryland.

The composition of a one-gallon sample of water taken during the summer months is given in Table IV, and except for temporary dilution due to unusually heavy rainfall or spring thaw, can be accepted as typical.

The ratio, epm. Mg^{++}/epm. Ca^{++}, is 4.83 for the Severn River water and 4.60 for sea water, indicating that these waters differ in concentration rather than constituents.

The test specimens were rectangular plates and hollow cylinders with finely machined surfaces and were completely submerged in water in wooden tanks or earthenware crocks of large capacity during the tests. Water pumped directly from the river to a large gravity tank flowed continuously to these containers. An auxiliary source of supply was available to avoid shut-downs due



EFFECT OF NICKEL SUBSTITUTIONS ON MICROSTRUCTURE
ETCHANT $NH_4OH + H_2O_2$
MAGNIFICATION X100

PLATE 8

TABLE IV

pH 8.17

COMPOSITION OF SEVERN RIVER WATER

Residue on evaporation 11,866 ppm.

Positive Ions	ppm.	epm.	Negative Ions	ppm.	epm.
Iron, Fe ++	Trace	Trace	Silicate, SiO_3- -	7.6	0.2
Calcium, Ca ++	137	6.86	Carbonate, CO_3- -	0.01	-
Magnesium, Mg ++	397	33.10	Bicarbonate, HCO_3-	85.3	1.4
Sodium, Na ++	3250*	141.74	Chloride, Cl-	5770	162.7
			Sulfate, SO_4- -	833	17.4

ppm = parts per million epm = equivalent parts per million

* By difference

to pump failure or necessary overhaul. A semi-automatic, thermostatically controlled steam heater maintained the temperature of the water between 75 and 85 degrees F.

The rectangular specimens were tested at zero velocity and at 30 feet per second; the cylindrical specimens were tested at 15 feet per second. A velocity of 30 feet per second is higher than normally encountered. The modified composition G alloy containing 6 per cent nickel was tested in the "as cast", the "aged" and the "annealed" conditions. The heat treatments were as follows: the "aged" samples were water quenched after 6 hours at 1400 degrees F. and aged 6 days at 700 degrees F.; the "annealed" samples were furnace cooled after 6 hours at 1400 degrees F. All other alloys were in the "as cast" condition.

(*a*) *Preparation of Test Specimens*

The specimens for the tests were cut from plates and hollow cylinders cast in green sand molds. The plates were 6 inches long by 4 inches wide by 1 inch thick, and the cylinders were 20 inches long by 2-3/8 inches outside diameter by 1 inch inside diameter. Strips cut from the plates were machined to 1/4 inch thick by 15/16 inch wide. Three specimens of each alloy were prepared from the plates; two were 6 inches long and one was 4 inches long. Holes were drilled at one end of these specimens for fastening in the corrosion apparatus. Specimens from the

cylinders were machined to 2-5/16 inch outside diameter, 1-1/2 inch inside diameter and 1-1/4 inch long.

(b) Method of Test

MOTIONLESS RECTANGULAR SPECIMENS

Two specimens, 6 inches long by 15/16 inch wide, of each alloy, spaced 3/4 inch apart, were suspended from glass rods in a large wooden tank of slowly moving Severn River water. The test pieces, which were motionless during the test, were removed from the tank after 40, 80 and 125 days, scrubbed with a bristle brush under tap water, dried and weighed.

ROTATING RECTANGULAR SPECIMENS

Specimens, 4 inches long by 15/16 inch wide, were bolted at 30 degree intervals on both sides of a micarta wheel 12 inches in diameter by 1/2 inch thick. The specimens on one side of the wheel were directly opposite those on the other side and projected 2 inches beyond the circumference of the wheel. The test pieces were held in place with 1/4 inch bolts and pins, one bolt and pin holding two specimens. The pins were made of hard rubber and the bolts were positively insulated from the specimens with a combined bushing and washer of micarta for each specimen.

The wheel was securely fastened to the center section of a horizontal monel metal line shaft which passed through a covered wooden tank fitted with stuffing-boxes. The section of shaft holding the wheel and specimens could be removed by means of flange couplings.

The shaft was revolved between 385 and 420 Rpm. At this speed, the velocity of the projecting ends of the specimens was between 28 and 31 feet per second. Only one specimen of each alloy was tested, as space was not available for duplicate samples.

The specimens were removed from the wheel after 28 and 69 days, scrubbed with a bristle brush in tap water, dried and weighed.

ROTATING CYLINDRICAL SPECIMENS

Four cylindrical specimens were assembled into pipes with a micarta ring between adjacent specimens and at each end of the

column. Each column of specimens was held concentrically on the reduced section of a monel metal shaft 1-1/4 inches in diameter by 12 inches long. Pressure from a nut at one end of the shaft forced the column against a shoulder and held the specimens tightly together. The micarta rings insulated the specimens from one another and from the shaft. Ordinary rubber bands were successfully used between the specimens and rings to obtain a water-tight joint.

Each shaft of four specimens was screwed onto the shaft of a vertically mounted motor and revolved at 1500 Rpm. At this speed, the surface velocity of the specimens was approximately 15 feet per second. After 28 days the specimens were removed, washed off under tap water, dried and weighed.

(*c*) *Discussion of Results*

MOTIONLESS RECTANGULAR SPECIMENS

The results of this test are shown graphically in Plate 10. The corrosion rate is expressed in milligrams per square inch per day. The open and the two hatched columns represent the successive test periods of 40, 80 and 125 days, respectively. The progressive replacement of tin by nickel produced no definite change in the corrosion rate of the compositions G and M in quiescent Severn River water. Heat-treatment had little effect on the corrosion rate of the 6 per cent nickel, 3 per cent tin alloy (G-2). A definite but small increase in the corrosion rate of the 85-5-5-5 alloy was produced by the substitution of 2.5 per cent nickel for an equal quantity of tin.

The character of the corrosion product which formed on these specimens is closely related to the composition of the alloy. Specimens of the regular compositions, that is, those containing no nickel, were covered with a thin, tenacious and protective film. As the tin content of the alloys was decreased and replaced by the equivalent in nickel, the corrosion film changed to a thin scale of low tenacity. The corrosion product was completely and easily removed from the one "tin-free" 9 per cent nickel alloy of the composition G group.

ROTATING RECTANGULAR SPECIMENS

The results of this test are shown graphically in Plate 11. The

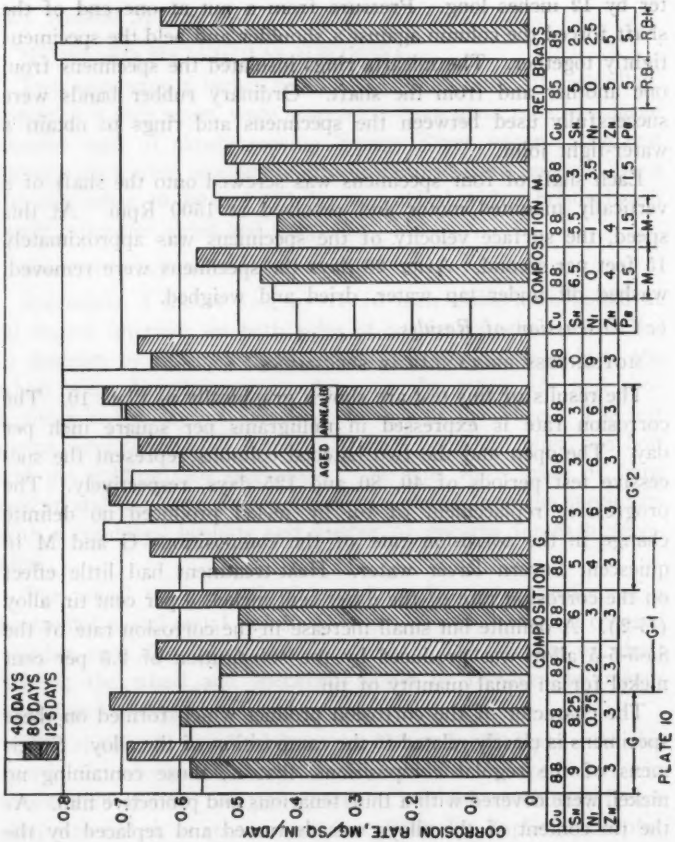


PLATE 10.—THE CORROSION RATE OF MOTIONLESS RECTANGULAR SPECIMENS OF STANDARD AND MODIFIED COMPOSITIONS G AND M AND RED BRASS IN SEVERN RIVER WATER.

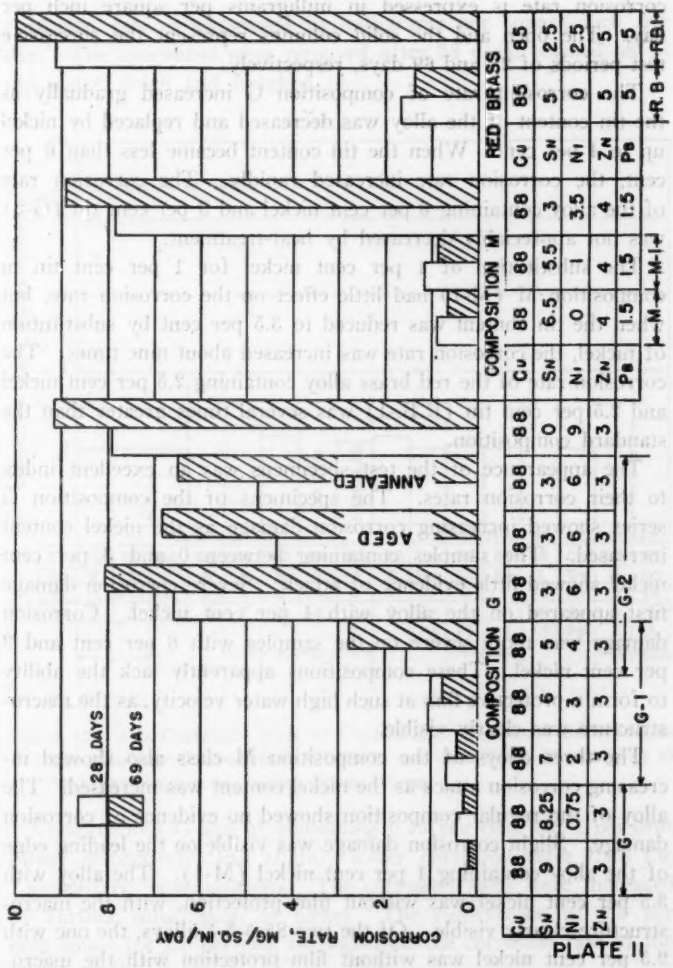


PLATE 11.—THE CORROSION RATE OF RECTANGULAR SPECIMENS OF STANDARD AND MODIFIED COMPOSITIONS G AND M AND RED BRASS ROTATED AT 30 FEET PER SECOND IN SEVERN RIVER WATER.

corrosion rate is expressed in milligrams per square inch per day. The open and the solid columns represent the successive test periods of 28 and 69 days, respectively.

The corrosion rate of composition G increased gradually as the tin content of the alloy was decreased and replaced by nickel up to 4 per cent. When the tin content became less than 6 per cent, the corrosion rate increased rapidly. The corrosion rate of the alloy containing 6 per cent nickel and 3 per cent tin (G-2) was not appreciably decreased by heat-treatment.

The substitution of 1 per cent nickel for 1 per cent tin in composition M (M-1) had little effect on the corrosion rate, but when the tin content was reduced to 3.5 per cent by substitution of nickel, the corrosion rate was increased about nine times. The corrosion rate of the red brass alloy containing 2.5 per cent nickel and 2.5 per cent tin (R.B.-1) was several times greater than the standard composition.

The appearance of the test specimens was an excellent index to their corrosion rates. The specimens of the composition G series showed increasing corrosion damage as the nickel content increased. The samples containing between 0 and 3 per cent nickel showed little evidence of attack. Severe corrosion damage first appeared on the alloy with 4 per cent nickel. Corrosion damage was more severe on the samples with 6 per cent and 9 per cent nickel. These compositions apparently lack the ability to form a protective film at such high water velocity, as the macrostructure was clearly visible.

The three alloys of the composition M class also showed increasing corrosion attack as the nickel content was increased. The alloy of the regular composition showed no evidence of corrosion damage. Slight corrosion damage was visible on the leading edge of the alloy containing 1 per cent nickel (M-1). The alloy with 3.5 per cent nickel was without film protection, with the macrostructure clearly visible. Of the two 85-5-5-5 alloys, the one with 2.5 per cent nickel was without film protection with the macrostructure revealed. The alloy of standard composition was not visibly damaged.

ROTATING CYLINDRICAL SPECIMENS

The results of this test are shown graphically in Plate 12. The

corrosion rate is expressed in milligrams per square inch per day. The specimens were removed after 28 days, washed off in tap water, dried and weighed.

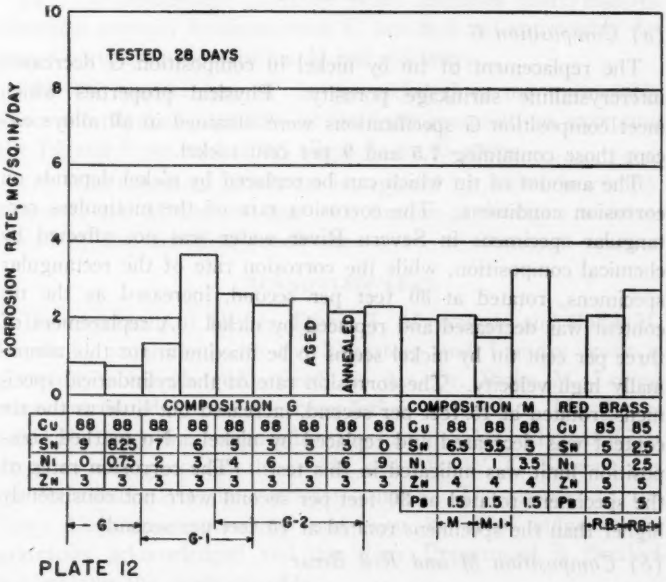


PLATE 12

PLATE 12.—THE CORROSION RATE OF CYLINDRICAL SPECIMENS OF STANDARD AND MODIFIED COMPOSITIONS G AND M AND RED BRASS REVOLVED AT 15 FEET PER SECOND IN SEVERN RIVER WATER.

Compositions G and M containing 0.75 per cent and 1 per cent nickel respectively, had slightly lower corrosion rates than the "nickel-free" compositions. The corrosion rates were increased by further substitution of nickel. The substitution of 2.5 per cent nickel for 2.5 per cent tin increased the corrosion rate of the 85-5-5-5 alloy.

The alloys with the lower corrosion rates were covered by a smooth, glazed film; those with higher rates were covered with a coarse, dull film. The least tenacious film formed on the specimens of the composition G group containing 6 per cent nickel

(G-2). Most of the film was removed from these specimens in cleaning. A dull red film completely covered the "tin-free", 9 per cent nickel, composition G alloy.

Summary.

(*a*) *Composition G*

The replacement of tin by nickel in composition G decreased intercrystalline shrinkage porosity. Physical properties which meet composition G specifications were obtained in all alloys except those containing 7.5 and 9 per cent nickel.

The amount of tin which can be replaced by nickel depends on corrosion conditions. The corrosion rate of the motionless rectangular specimens in Severn River water was not affected by chemical composition, while the corrosion rate of the rectangular specimens, rotated at 30 feet per second, increased as the tin content was decreased and replaced by nickel. A replacement of three per cent tin by nickel seems to be maximum for this abnormally high velocity. The corrosion rate of the cylinderical specimens, rotated at 15 feet per second, increased but little as the tin content was decreased and replaced by nickel. No marked composition limit was indicated in this test. (The corrosion rates of the specimens rotated at 30 feet per second were not consistently higher than the specimens rotated at 15 feet per second).

(*b*) *Composition M and Red Brass*

The replacement of tin by nickel in composition M and red brass did not effectively decrease intercrystalline shrinkage porosity, while all alloys met the physical property requirements for their respective basis compositions.

The corrosion rate of the motionless rectangular specimens in Severn River water was not affected by variations in the chemical composition of composition M, but showed a definite, although slight, increase when 2.5 per cent tin was replaced by 2.5 per cent nickel in red brass (R.B.-1). The corrosion rate of the rectangular specimens, rotated at 30 feet per second, definitely increased when 3.5 per cent tin was replaced by 3.5 per cent nickel in composition M, and when 2.5 per cent tin was replaced by 2.5 per cent nickel in red brass. A noticeable, but slight, increase in the corrosion rate of the cylindrical specimens was noted when the

last two above mentioned alloys were revolved at 15 feet per second.

Conclusions.

(a) The replacement of tin by nickel decreases intercrystalline shrinkage porosity in composition G, but does not appreciably decrease porosity in composition M and red brass.

(b) The replacement of tin by nickel does not appreciably lower the physical properties of the basic compositions excepting the 7.5 and 9 per cent nickel alloys in the G series.

(c) The extent to which tin is replaced by nickel in compositions G and M and red brass for marine applications is determined by the corrosion conditions.

Acknowledgment.

The assistance of Messrs. Edwin T. Myskowski and Ralph H. Brouk in connection with the laboratory and foundry work is gratefully acknowledged. Credit is due Dr. Blake M. Loring who contributed toward the compilation of the data, Mr. James L. Darby who was responsible for melting, Mr. Thomas Cunningham who prepared the molds, and Mr. W. C. Stewart for his contributions to the corrosion studies. The support of the Navy Department personnel and men in allied industries is gratefully acknowledged and the Navy Department is thanked for making the work possible.

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THE HULL AND ITS SCREW PROPELLER.

By E. A. Stevens, Jr., Member.

Part 5—Cavitation.

No lengthy description of the subject known as cavitation will be made, the purpose being to give the reader such information so that it can be determined if the propeller is operating in cavitation or not, and if so what may be expected, and how to cure the trouble.

There are two kinds of cavitation which may be designated as tip speed and thrust cavitation, which will be discussed in the order given.

TIP SPEED CAVITATION.

This is true cavitation and the type first encountered in 1894 on the trials of the British destroyer *Daring*. It was brought to the attention of the engineering profession by Mr. Sidney W. Barnaby, who gave it the name cavitation. In order to eliminate this, when the diameter is sufficient, it is necessary to widen the blades. This can be done by increasing the area or by reducing the number of blades. In the latter case, the total area can, in some cases, be reduced. If the propeller is operating in thrust as well as tip speed cavitation, the diameter should also be increased, but if not operating in thrust cavitation increasing the diameter will be of no help.

When the standard form of projected area and blade sections (similar to Section A in Figure 6) are used, tip speed cavitation will commence when the actual Rpm. (R_a) of 3-bladed propellers equals the basic Rpm. (R) and 95 per cent of the basic revolutions with propellers with 4 blades. If the following edge is thrown back as in Section C tip speed cavitation will probably start somewhat earlier.

In some cases trial data of destroyers fitted with propellers with ogival sections (Section A of Figure 6), where the value of $1\text{-}S_B$ is reduced at the higher speeds due to squatting, indicate that tip speed cavitation does not commence until the revolutions reach a higher value than the basic revolutions (R). On the other hand, however, trial data of other destroyers, also fitted with propellers with ogival sections, where the value of $1\text{-}S_B$ is reduced due to squatting, show cavitation starting at or very close to revolutions equal to the basic Rpm.

The Influence of the Shape of the Projected Area and Blade Section on Tip Speed Cavitation.

When the shape of the projected area and/or the blade sections differ from the standard, the revolutions at which tip speed cavitation starts will vary from those already given. As there is not sufficient data available to determine the influence of the shape of the projected area or the blade sections, the following rules should be considered as approximations.

Shape of the Projected Area.

Narrow Tip Blades.—When dealing with blades of this type, the equivalent standard projected area ratio should be obtained as described in PART 4. The revolutions at which cavitation starts will be equal to the basic Rpm. corresponding to a projected area ratio between the equivalent standard and the actual projected area ratio of three blades.

Let P.A. $\div$ D.A. = equivalent standard projected area ratio of 3 blades

P.A.′ $\div$ D.A.′ = actual projected area ratio of 3 blades

P.A.″ $\div$ D.A.″ = projected area ratio of 3 blades for obtaining the Rpm. at which cavitation starts

$$\text{P.A.}'' \div \text{D.A.}'' = \frac{2(\text{P.A.} \div \text{D.A.}) + (\text{P.A.}' \div \text{D.A.}')}{3}$$

This rule may also be used when dealing with Bulbous Tip Blades when the shape of the blade from the .7 radius to the tip does not materially differ from the standard.

Blades Tips Broader Than Standard.—When the propeller has blades with broader tips than the standard (Figures 4A and 4B) use the actual projected area ratio of three blades for obtaining the value of TS $\div$ π and the actual diameter (D_1) to determine the revolutions at which cavitation starts.

Blade Section.

Sections B.C. and D. of Figure 6.—when the leading edge is thrown back from the driving face, as shown in Sections B and C, the revolutions at which tip speed cavitation starts will be somewhat higher than if Section A was used. Section D when the greatest distance from the driving face to the pitch line at the .2 radius is not more than .35 to .40 of the width of the blade (at this radius) from the leading edge, can be considered as one where the pitch is less than that of the pitch line (as explained in PART 4 and on Figure 6A), and with the leading edge thrown back from the driving face.

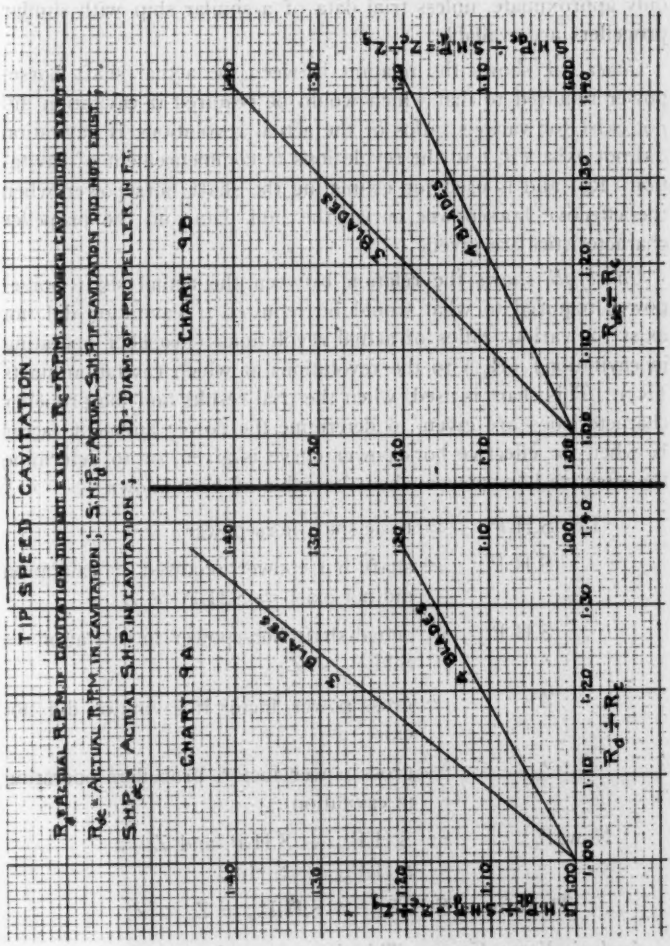
Section E.—It is questionable if any advantage can be had by the use of this section when the curvature on the driving face is not great, and especially when the greatest distance from the driving face to the pitch line at the .2 radius is more than .4 of the blade width at this radius from the leading edge.

Section F.—When the leading edge is rounded as in this section, the revolutions at which cavitation starts will be somewhat (probably not over 5 per cent) greater than those when Section A is used.

Section G.—Trial data have shown that, when the throw-back (or lift) of the leading edge at the .2 radius is approximately 40 per cent (or greater) of the maximum thickness at that radius, cavitation will start at approximately 15 per cent higher revolutions than for similar blades with ogival sections (at the .2 radius). That is, cavitation will start at approximately 1.15 $\times$ R for 3-bladed propellers and 1.09 $\times$ R for 4-bladed wheels (R being the basic Rpm.).

Method Used in Estimating Shaft Horsepower and Rpm. When Propellers Are Operating in Tip Speed Cavitation.

Considering the difficulties of determining the revolutions at which tip speed cavitation starts and as the performances of pro-


TIP SPEED CAVITATION
CHART 9A
CHART 9B
3 BLADES
4 BLADES
5 BLADES
6 BLADES

pellers operating in this condition are quite erratic, any estimate of the expected power and revolutions should be considered as only approximate, unless trial data of a similar ship with similar propellers are available.

Chart 9A shows the relation between the actual shaft horsepower required to that which would be required if cavitation did not exist for various ratios of the actual revolutions if cavitation did not exist (R_d) to the revolutions at commencement of cavitation (R_c) and is used for estimating the shaft horsepower when the effective horsepower curve, the hull data and the propeller characteristics are given.

Chart 9B shows the relation between the actual shaft horsepower required to what would be required if cavitation did not exist for various ratios of actual revolutions (propeller operating in cavitation) (R_{dc}) to the revolutions at which cavitation starts (R_c). This chart is used, when the trial results and the propeller characteristics are given, to determine the power augment factor K when the effective horsepower curve is given, or to determine the effective horsepower when the value of K is known.

Let S.H.P. = basic shaft horsepower

$S.H.P._d$ = shaft horsepower required if cavitation did not exist = S.H.P. $\times$ Z_g

$S.H.P._{dc}$ = actual shaft horsepower in cavitation = S.H.P. $\times$ Z_c

Z_g = gross power factor if cavitation did not exist

Z_c = gross power factor, propellers operating in cavitation

Now Z_g = $S.H.P._d \div$ S.H.P. and Z_c = $S.H.P._{dc} \div$ S.H.P.

Therefore $S.H.P._{dc} \div S.H.P._d = Z_c \div Z_g$

Analysis Form No. 4.—This form is used when the hull data, e.h.p. curve and propeller characteristics are given and it is desired to predict the performance, which is done as follows:

PROPELLER ANALYSIS IN TIP SPEED CAVITATION

ANALYSIS FORM N° 4

GIVEN: K , $1-S_B$ and e.h.p. Curve
FIND : Actual S.H.P ($S.H.P_{dc}$) and Actual R.P.M. (R_{dc})

8	R	From Basic Conditions
10	$V/1-S_B$	" " "
13	N x S.H.P.	" " "
17	N x E.H.P.	" " "
18	$1-S_B$	" " "
19	K	" " "
20	R_c = R.P.M. at which cavitation starts.	
21	v = Actual Speed in Knots	
22	$v \div V/1-S_B$ = (21) ÷ (10)	
23	N x e.h.p. From e.h.p. Curve = Actual e.h.p. on all shafts.	
24	e.h.p ÷ E.H.P. = N x e.h.p ÷ N x E.H.P = (23) ÷ (17)	
25	Z From TABLE II	
26	$Z_q = Z \times K$ = (25) x (19)	
27	$N \times S.H.P_q = N \times S.H.P \times Z_q$ = (13) x (26) = Actual S.H.P. if Cavitation did not exist	
28	$v \div V = (v \div V/1-S_B) \div (1-S_B)$ = (22) ÷ (18)	
29	Y From CHART 8A ($v \div V$ Line 28 as abscissa)	
30	Z_R From CHART 8A (Z_q " 26 " ")	
31	$R_d \div R = Y \times Z_R$ = (29) x (30)	
32	$R_d = R \times (R_d \div R)$ = (8) x (31)	
	If R_d is greater than R_c (Line 20) Tip Speed Cavitation exists.	
33	$R_d \div R_c$ = (32) ÷ (20)	
34	$Z_c \div Z_q$ From CHART 9A	
35	$Z_c = Z_q \times (Z_c \div Z_q)$ = (26) x (34)	
36	$N \times S.H.P_{dc} = N \times S.H.P \times Z_c$ = (13) x (35) = Actual S.H.P. on all shafts.	
37	Z_{RC} From CHART 8A (Z_c Line 35 as abscissa)	
38	$R_{dc} \div R = Y \times Z_{Rc}$ = (29) x (37)	
39	$R_{dc} = R \times (R_{dc} \div R)$ = (8) x (38) = Actual R.P.M.	
	For high speed vessels which squat when being driven, use the following modification of the above Form.	
	$v \div V.L.W.L$	
a	S.C.F. From CHART 5 F = $1-S_B$ Correction Factor for Squatting	
18a	$1-S_{Ba} = (1-S_B) \times S.C.F.$ = (18) x (a)	
28	$v \div V = (v \div V/1-S_B) \div (1-S_{Ba})$ = (22) ÷ (18a)	
	Lines 29 to 39 inclusive are the same as above.	

First: Estimate the power and revolutions required as if the propeller was not operating in cavitation. If the estimated revolutions under these conditions (R_d line 32) are greater than those at which cavitation starts (R_c line 20) the propeller will be operating in cavitation.

Second: Turn to Chart 9A and obtain the power correction factor for cavitation ($Z_c \div Z_g$). Z_c will then equal Z_g (line 26) $\times$ ($Z_c \div Z_g$) and the actual shaft horsepower in cavitation (S.H.P.$_{dc}$) = S.H.P. $\times$ Z_c (See line 36) or S.H.P.$_{dc}$ = S.H.P.$_d$ (Line 27) $\times$ ($Z_c \div Z_g$).

The actual Rpm. when operating in cavitation are obtained in the same manner as if cavitation did not exist except that Z_c is used as the abscissa in place of Z_g in obtaining the revolution factor Z_{Rc} from Chart 8A.

Analysis Forms No. 5 and No. 6.—If the trial performance is to be analyzed to obtain the value of K, Form No. 5 is used. If it is desired to obtain the actual effective horsepower, K being known (or estimated from the hull analysis), Form No. 6 is used.

Having the ratio of the actual revolutions (R_{dc}) to the revolutions at which cavitation starts (R_c), the power correction favor ($Z_c \div Z_g$) is obtained from Chart 9B. The power factor Z_g is obtained on line 28 of Analysis Form No. 5 or No. 6. The value of K or e.h.p, as the case may be, is then obtained as shown on these forms.

The value of 1-S_B is obtained in the same manner as if the propeller was not in cavitation except Z_c is used as the abscissa in place of Z_g in obtaining the revolution factor Z_{Rc} from Chart 8A.

THRUST CAVITATION.

This type of cavitation was given its name by Admiral Dyson. This expression, however, is not quite correct as this phenomenon occurs at low as well as high thrusts. It is caused by too small a diameter and too great a pitch for the conditions under which the propeller is operating.

If a propeller having an infinite pitch (that is when the plane of the face of the blades passes through the center line of the shaft) is revolved, it would merely act as a centrifugal pump pro-

PROPELLER ANALYSIS IN TIP SPEED CAVITATION

ANALYSIS FORM N° 5

GIVEN – Actual S.H.P. ($S.H.P_d$) and Actual R.P.M. (R_d) from Trial Data and e.h.p. curve

FIND Power Augment Factor (K) and 1 – Basic Slip ($1-S_B$)

8	R From Basic Conditions
10	$V/1-S_B$ " " "
13	N x S.H.P. " " "
17	N x E.H.P " " "
18	$1-S_B$ " " "
19	K " " "
20	R_c = R.P.M. at which cavitation starts
21	v = Actual Speed in Knots.
22	$v \div V/1-S_B$ = (21) ÷ (10)
23	N x S.H.P_{dc} = Actual S.H.P. on all shafts. From Trial Data.
24	Z_c = N x S.H.P_{dc} ÷ N x S.H.P = (23) ÷ (13)
25	R_{dc} = Actual R.P.M. From Trial Data.
26	$R_{dc} \div R_c$ = (25) ÷ (20)
27	$Z_c \div Z_q$ From CHART 9
28	$Z_q = Z_c \div (Z_c \div Z_q)$ = (24) ÷ (27)
29	N x e.h.p From e.h.p. Curve = Actual e.h.p. on all shafts
30	e.h.p ÷ E.H.P = N x e.h.p ÷ N x E.H.P = (29) ÷ (17)
31	Z From TABLE II
32	$K = Z_q \div Z$ = (28) ÷ (31)
33	$R_{dc} \div R$ = (25) ÷ (8)
34	Z_{RC} From CHART 8A (Z_c Line 24 as abscissa)
35	$Y = (R_{dc} \div R) \div Z_{RC}$ = (33) ÷ (34)
36	$v \div V$ From CHART 8A (Y Line 35 as ordinate)
37	$1-S_B = (v \div V/1-S_B) \div (v \div V)$ = (22) ÷ (36)

ANALYSIS FORM N° 6

GIVEN – Actual S.H.P. ($S.H.P_d$) and Actual R.P.M. (R_d) from Trial Data and Power Augment Factor (K)

FIND Actual E.H.P. (e.h.p) and $1-S_B$

Lines 7 to 28 inclusive same as in Form N° 5

29	$Z = Z_q \div K$ = (28) ÷ (19)
30	e.h.p ÷ E.H.P From TABLE II
31	N x e.h.p. = (N x E.H.P) x (e.h.p ÷ E.H.P) = (17) X (30)
32	$R_{dc} \div R$ = (25) ÷ (8)
33	Z_{RC} From CHART 8A (Z_c Line 24 as abscissa)
34	$Y = (R_{dc} \div R) \div Z_{RC}$ = (32) ÷ (33)
35	$v \div V$ From CHART 8A
36	$1-S_B = (v \div V/1-S_B) \div (v \div V)$ = (22) ÷ (35)

ducing no thrust. Should the pitch be reduced slightly, the propeller would deliver some thrust, but the greater part of the power would be wasted in giving the discharge column of water a rotating motion. As the pitch is decreased, the thrust delivered will increase, the rotation of the discharge column decrease, and the propulsive efficiency will improve until a given pitch, depending upon conditions, is reached.

When thrust cavitation exists, it can be reduced and sometimes eliminated by decreasing the pitch and increasing the diameter and/or the revolution. If it is not possible to increase the diameter or revolutions, the blade tips should be made wider. If the propeller has sufficient area to keep it out of tip speed cavitation, increasing the area will not help unless this additional area is added at the tips of the blades. Should the propeller have considerably more area than is necessary to keep it out of tip speed cavitation, a reduction of the area will be helpful, provided this reduction is not made near the tips of the blades.

Chart 9C.—This chart is used to determine if a propeller is operating in thrust cavitation or not. With Z_g or Z_c as the abscissa and $v \div V/1\text{-}S_B$ as the ordinate, plot the performance on this chart. If it falls below Curve 1 or 2, as the case may be, the wheel is operating in thrust cavitation.

RULES FOR THE USE OF CURVE 1 OR 2 ON CHART 9C.

Vessels of Types 1, 2 and 3.—When the value of $1\text{-}S_B$ is less than .80, use Curve 2.

This rule does not apply to high speed vessels where the value of $1\text{-}S_B$ before squatting occurs is greater than .80, but at high speeds is reduced due to squatting nor for vessels of Type 4. For such vessels, the rules given below should be followed.

When the Value of $1\text{-}S_B$ Is Greater Than .80 Twin and Four Screw Vessels.

Vessels of Type 1 and Between Types 1 and 3.—Ships with cruiser sterns where the L.W.L. plane covers one-half or more of the propellers (L.W.L. "A", Sketch "B", Chart 4A) use Curve 1.

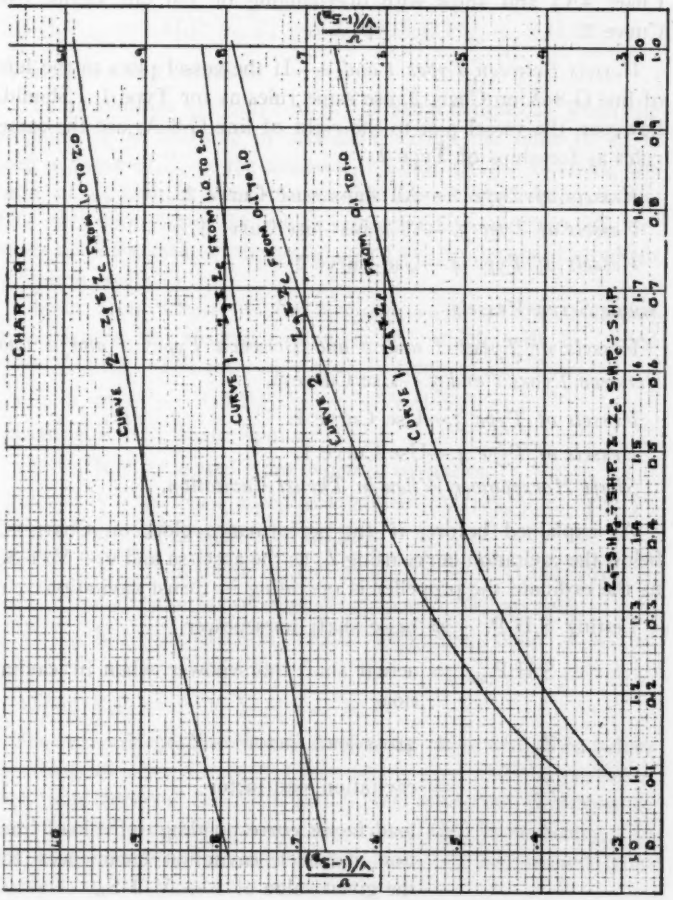


CHART 9C
CURVE 2 $Z_2 = Z_1 \frac{V_c}{V}$ FROM 1.0 TO 2.0
CURVE 1 $Z_1 = Z_2 \frac{V}{V_c}$ FROM 1.0 TO 2.0
CURVE 2 $Z_2 = Z_1 \frac{V_c}{V}$ FROM 0.1 TO 1.0
CURVE 1 $Z_1 = Z_2 \frac{V}{V_c}$ FROM 0.1 TO 1.0
$Z_1 = S.H.P. \times Z_2 \div S.H.P.$
$\frac{(S-1)}{V}$
$\frac{(S-1)}{V}$

Ships with cruiser sterns where the L.W.L. plane does not cover one-half of the propellers (L.W.L. "B", Sketch "B", Chart 4A) and ships with overhanging or fan tail sterns, use Curve 2.

Vessels Between Types 1 and 2.—If the vessel plots to the left of line G-8-A on Chart 3, use same rules as for Type 1. Should, however, the vessel plot to the right of line G-8-A, use the same rules as for ships of Type 2.

Vessels of Type 2.—All ships—use Curve 2.

Vessels of Type 3.—All ships—use Curve 1.

Vessels of Type 4.—Use Curve 1.

Single Screw Vessels.

Vessels of Types 1 and 2 and Between Types 1 and 2 and Between Types 1 and 3.—Use Curve 2.

Vessels of Type 3.—Use Curve 1.

Vessels of Type 4.—Use Curve 1.

Shaft Horsepower When in Thrust Cavitation.

As explained before, if the performance plots on Chart 9C below the cavitation curve using Z_g as the abscissa and $v \div V/1\text{-}S_B$ as the ordinate the propeller is operating in thrust cavitation.

Letting S.H.P. = basic shaft horsepower

$S.H.P._{dc}$ = actual shaft horsepower when in cavitation

Z_g = gross load factor = $Z \times K$

Z_c = cavitation load factor

Z_1 = load factor corresponding to the load fraction at which cavitation commences for the given value of $v \div V/1\text{-}S_B$

From Chart 9C obtain the abscissa value of the curve to be used where its ordinate value is $v \div V/1\text{-}S_B$. This will be the value of Z_1.

Then $S.H.P._{dc} = S.H.P. \times Z_g^2 \div Z_1$

Letting $Z_g^2 \div Z_1 = Z_c$ we have

$S.H.P._{dc} = S.H.P. \times Z_c$ and $Z_c = S.H.P._{dc} \div S.H.P.$

Rpm. When in Cavitation.

The revolutions are obtained in the same manner as when the propeller is not working in cavitation, except the value of Z_c is used in place of Z_g as the abscissa of Chart 8A for obtaining the value of Z_R and, in certain cases, the use of a correction factor. This correction factor M, which is obtained from Chart 8C, depends upon the ratio of the actual speed (v) to the speed at which cavitation starts (v_c).

Obtain from Chart 9C the ordinate value of the cavitation curve where its abscissa value is Z_c which will be called $v_c \div V/1\text{-}S_B$. The ratio of v to v_c is obtained as follows:

$v \div v_c = (v \div V/1\text{-}S_B) \div (v_c \div V/1\text{-}S_B)$

Letting R = basic Rpm.

R_{dc} = actual Rpm. when in cavitation

V = basic speed in knots $= (V/1\text{-}S_B) \div (1\text{-}S_B)$

v = actual speed in knots

Y = a factor depending upon $v \div V$ (Chart 8A)

Z_{Rc} = a factor depending upon Z_c (Chart 8A)

M = correction factor depending upon $v \div v_c$ (Chart 8C)

Then $R_{dc} = R \times Y \times Z_{Rc} \times M$

The correction factor M is not used for ships with $1\text{-}S_B$ values less than .95 when Curve 2, Chart 9C, is used and the performance plots between Curves 1 and 2, but when the performance plots below Curve 1 this correction factor (M) is necessary. In this case, however, the value of $v_c \div V/1\text{-}S$ is obtained from Curve 1.

Rules for Obtaining the Value of "M" from Chart 8C.

Use Z_c as the abscissa value in obtaining the value of $v_c \div V/1\text{-}S_B$ from Chart 9C.

Let $v_{c1} \div V/1\text{-}S_B$ = ordinate value of Curve 1, Chart 9C

$v_{c2} \div V/1\text{-}S_B$ = ordinate value of Curve 2, Chart 9C

Then $v \div v_{c1} = (v \div V/1\text{-}S_B) \div (v_{c1} \div V/1\text{-}S_B)$

and $v \div v_{c2} = (v \div V/1\text{-}S_B) \div (v_{c2} \div V/1\text{-}S_B)$

All Ships using Curve 1.

$$R_{dc} = R \times Y \times Z_{Rc} \times M$$

Use $v \div v_{c1}$ as abscissa in obtaining M from Chart 8C.

Ships using Curve 2 where 1-S_B is greater than .95.

$$R_{dc} = R \times Y \times Z_{Rc} \times M$$

Use $v \div v_{c2}$ as abscissa in obtaining M from Chart 8C.

Ships using Curve 2 where 1-S_B is less than .95.

If the performance plots between Curve 1 and Curve 2, Chart 9C.

$$R_{dc} = R \times Y \times Z_{Rc} \text{ (no correction)}$$

If the performance plots below Curve 1, Chart 9C.

$$R_{dc} = R \times Y \times Z_{Rc} \times M$$

Use $v \div v_{c1}$ as abscissa in obtaining M from Chart 8C.

Analysis Form No. 7.—This form is used when the e.h.p. curve and the data of the hull and propeller is given and it is desired to make an estimate of the vessel's performance. It will be noticed that this form is the same as Analysis Form No. 1 down to and including line 25, at which point it can be determined if the propeller is or is not operating in thrust cavitation.

Analysis Forms Nos. 8 and 9.—Form No. 8 is used when the e.h.p. curve, the propeller characteristics and trial data are given and it is desired to find the value of K. Form No. 9 is used when the value of e.h.p. is to be obtained, from the trial data, the characteristics of the propeller and the value of K being known. The value of 1-S_B can be obtained from either form. A comparison of these forms and Forms Nos. 2 and 3 will show them to be the same down to and including line 23 except that $N \times S.H.P._d$ and Z_g have been replaced by $N \times S.H.P._{dc}$ and Z_c. At this point (line 23) it can be determined if the propeller is operating in cavitation or not. If the performance plots above the cavitation

PROPELLER ANALYSIS IN THRUST CAVITATION

ANALYSIS FORM N°7

GIVEN - K , $1-S_B$ and e.h.p Curve

FIND - Actual S.H.P. ($S.H.P_{dc}$) and Actual R.P.M. (R_{dc})

8	R	From Basic Conditions
10	$V/1-S_B$	" " "
13	N x S.H.P	" " "
17	N x E.H.P	" " "
18	$1-S_B$	" " "
19	K	" " "
20	v = Actual Speed in Knots	
21	$v \div V/1-S_B = (20) \div (10)$	
22	N x e.h.p From e.h.p. Curve = Actual e.h.p. on all shafts	
23	e.h.p ÷ E.H.P = N x e.h.p ÷ N x E.H.P = (22) ÷ (17)	
24	Z From TABLE II	
25	$Z_q = Z \times K = (24) \times (9)$	If performance plots below the cavitating curve (Curve 1 or 2 on CHART 9C) the propeller is in Thrust Cavitation
26	Z_1	Abscissa value of cavitation curve on CHART 9C where ordinate is $v \div V/1-S_B$ (Line 21)
27	$Z_q^2 = (25)^2$	
28	$Z_c = Z_q^2 \div Z_1 = (27) \div (26)$	
29	$N \times S.H.P_{dc} = N \times S.H.P \times Z_c = (13) \times (28)$ = Actual S.H.P on all shafts	
30	$V_a \div V/1-S_B$ From CHART 9C = Ordinate value of cavitation curve where abscissa is Z_c (Line 28)	
31	$v \div v_c = (v \div V/1-S_B) \div (V_c \div V/1-S_B) = (21) \div (30)$	
32	M From CHART 8C	
33	$v \div V = (v \div V/1-S_B) \div (1-S_B) = (21) \div (18)$	
34	Y From CHART 8A ($v \div V$ Line 33 as abscissa)	
35	Z_{Rc} From CHART 8A (Z_c Line 28 as abscissa)	
36	$R_{dc} \div R = Y \times Z_{Rc} \times M = (34) \times (35) \times (32)$	
37	$R_{dc} = R \times (R_{dc} \div R) = (8) \times (36)$	

For high speed vessels, which squat when being driven, use the following modification of the above Form

	$v \div VL.W.L$	
a	S.C.F_S From CHART 5F = $1-S_B$ Correction Factor for Squatting	
18a	$1-S_{Ba} = (1-S_B) \times$ S.C.F_S = (18) x (a)	
33	$v \div V = (v \div V/1-S_B) \div (1-S_{Ba}) = (21) \div (18a)$	
34	Y From CHART 8A ($v \div V$ Line 33 as abscissa)	
35	Z_{Rc} From CHART 8A (Z_c Line 28 as abscissa)	
36	$R_{dc} \div R = Y \times Z_{Rc} \times M = (34) \times (35) \times (32)$	
37	$R_{dc} = R \times (R_{dc} \div R) = (8) \times (36)$	

PROPELLER ANALYSIS IN THRUST CAVITATION

ANALYSIS FORM N°8

GIVEN : Actual S.H.P.($S.H.P_{dc}$) and Actual R.P.M. (R_{dc}) from Trial Data and e.h.p. curve.

FIND : Power Augment Factor (K) and 1-Basic Slip ($1-S_B$)

8	R	From Basic Conditions
10	$V/1-S_B$	" " "
13	N x S.H.P.	" " "
17	N x E.H.P.	" " "
18	$1-S_B$	" " "
19	K	" " "
20	v	= Actual Speed in Knots
21	$v \div V/1-S_B$	= (20) ÷ (10)
22	N x $S.H.P_{dc}$	From Trial Data = Actual S.H.P on all shafts.
23	$Z_c = N \times SHP_d \div N \times SHP$	= (22) ÷ (13) If performance plots below cavitation curve (Curve 2) on CHART 9C Propeller is operating in cavitation.
24	Z_1	From CHART 9C Abscissa value of cavitation curve where ordinate is $v \div V/1-S_B$ (Line 21)
25	$Z_4 = Z_c \times Z_1$	= (23) x (24)
26	Z_4	= Y(35)
27	N x e.h.p	From e.h.p. curve = Actual e.h.p. on all shafts for speed v (Line 20)
28	e.h.p ÷ E.H.P	= N x e.h.p ÷ N x E.H.P. = (27) ÷ (17)
29	Z	From TABLE II
30	$K = Z_4 \div Z$	= (26) ÷ (29)
31	$V_c \div V/1-S_B$	From CHART 9C Ordinate value of cavitation curve where the abscissa is Z_c (Line 23)
32	$v \div V_c$	= $(v \div V/1-S_B) \div (V_c \div V/1-S_B)$ = (21) ÷ (31)
33	M	From CHART 8C
34	R_{dc}	From Trial Data = Actual R.P.M.
35	$R_{dc} \div R$	= (34) ÷ (8)
36	Z_{Rc}	From CHART 8A (Z_c Line 23 as abscissa)
37	$Z_{Rc} \times M$	= (36) x (33)
38	Y	= $(R_{dc} \div R) \div (Z_{Rc} \times M)$ = (35) ÷ (37)
39	$v \div V$	From CHART 8A (Y Line 38 as ordinate)
40	$1-S_B$	= $(v \div V/1-S_B) \div (v \div V)$ = (21) ÷ (39)

ANALYSIS FORM N°9

GIVEN : Actual S.H.P ($S.H.P_{dc}$) and Actual R.P.M. (R_d) from Trial Data and Power Augment Factor (K)

FIND : Actual E.H.P. (e.h.p.) and 1-Basic Slip ($1-S_B$)

Lines 7 to 26 inclusive Same as in Form N°8

27	Z	= $Z_4 \div K$ = (26) ÷ (19)
28	e.h.p ÷ E.H.P.	From TABLE II
29	N x e.h.p.	= N x E.H.P. x (e.h.p ÷ E.H.P) = (17) x (28) = Total Actual e.h.p. on all shafts
30	$V_c \div V/1-S_B$	From CHART 9C = Ordinate value of cavitation curve where the abscissa is Z_c (Line 23).
31	$v \div V_c$	= $(v \div V/1-S_B) \div (V_c \div V/1-S_B)$ = (21) ÷ (30)
32	M	From CHART 8C
33	R_{dc}	From Trial Data = Actual R.P.M.
34	$R_{dc} \div R$	= (33) ÷ (8)
35	Z_{Rc}	From CHART 8A (Z_c Line 23 as abscissa)
36	$Z_{Rc} \times M$	= (35) x (32)
37	Y	= $(R_{dc} \div R) \div (Z_{Rc} \times M)$ = (34) ÷ (36)
38	$v \div V$	From CHART 8A (Y Line 37 as ordinate)
39	$1-S_B$	= $(v \div V/1-S_B) \div (v \div V)$ = (21) ÷ (38)

curve thrust cavitation is not present and lines 22 and 23 should be N $\times$ S.H.P.$_d$ and Z_g and Form No. 2 or No. 3 used. If, however, the performance plots below the cavitation curve, lines 22 and 23 should be N $\times$ S.H.P.$_{dc}$ and Z_c and Form No. 8 or No. 9 followed.

PROPELLERS IN BOTH TIP SPEED AND THRUST CAVITATION.

Admiral Dyson stated that thrust cavitation absorbs tip speed cavitation and when the propeller is operating in both, the latter should be neglected. It appears to the writer, however, that a safer course to follow when estimating the prospective performances, is to make two estimates, one as if the propeller was operating in thrust cavitation only, the other as if only tip speed cavitation existed, and use the one giving the higher shaft horsepower.

PART 6—DESIGN CALCULATIONS.

Design calculations are the reverse of those for analyses. In the latter, the characteristics of the propeller are given, from which the basic conditions and then the expected results are calculated.

In design problems the desired speed and actual effective horsepower and revolutions are given from which the power required and the characteristics of the propeller are obtained, or the effective horsepower curve, actual shaft horsepower and revolutions are given, it being desired to find the characteristics of the propeller and the speed that may be expected. The procedure is as follows:

Chose values of Z_g and v $\div$ V/1-S_B. The basic effective horsepower (E.H.P.), basic shaft horsepower (S.H.P.), basic speed (V), basic revolutions (R) and basic propulsive coefficient (P.C.) are calculated, from which the characteristics of the propeller and the expected shaft horsepower or speed are obtained. The steps taken in this procedure are shown in Design Forms Nos. 1, 2, 3 and 4.

If the design is for an existing ship or for one building, where the position of the propeller centers have been determined, the

height of the center of the propellers above the base line (h) is known. If, however, the shaft center has not been located, it is necessary, in order to obtain the value of $1\text{-}S_B$, to approximate its height above the base line which is done as follows:

Divide the cube root of the actual shaft horsepower on one shaft by the Rpm. ($\sqrt[3]{S.H.P._d \div R_d}$). Turn to Chart 2C and obtain the approximate diameter of the propeller. Add to half this diameter the desired height of the lower tip above the base line (h') the resultant value ($D/2 + h'$) being the approximate value of h to use for h/H in obtaining the correction factor $S.C.F._h$ from Chart 5C or 5E, from which the values of $1\text{-}S_B$ are obtained for the preliminary calculations. The value of h' for single screw ships can be approximated (if not known) from Chart 2B and the value of H' obtained by adding the diameter of the propeller (D) as obtained from Chart 2C.

If the dimensions, displacement and midship section coefficient for a new ship have been determined, but the lines have not been drawn, the value of the effective length of after body (L.A.B.) can be estimated from Chart 2A (See L.A.B. in Part 2).

After the values of K and $1\text{-}S_B$ have been determined, the first step is to choose the values of Z_g and $v \div V/1\text{-}S_B$. This choice is very important. The higher the value of Z_g, the smaller will the value of P.A. ÷ D.A. and the higher the propulsive efficiency, providing this value for three blades is not less than .23. Should the calculated value of the projected area ratio of three blades (P.A. ÷ D.A.) be less than .23, lower values of Z_g and $v \div V/1\text{-}S_B$ should be chosen and new calculations made. These values, namely, Z_g and $v \div V/1\text{-}S_B$ should be selected so that the point will plot on Chart 9C sufficiently above Curve 1 or 2 (as the case may be) to prevent the propeller entering thrust cavitation when conditions are somewhat worse than those for which the propeller is designed, and at the same time not in tip speed cavitation. In order to shorten the work in making this selection, Chart 8B has been prepared.

After assuming values for Z_g and $v \div V/1\text{-}S_B$ the value of $v \div V$ is obtained by dividing $v \div V/1\text{-}S_B$ by $1\text{-}S_B$. With the value of $v \div V$ as abscissa, enter Chart 8B and run up till the curve corresponding to the chosen value of Z_g is reached, the ordi-

nate being the value of $R_d \div R$. If this value is greater than or too close to that at which tip speed cavitation starts, lower values of $v \div V/1\text{-}S_B$ and/or Z_g should be taken.

Although experience is the best guide for determining the values of Z_g and $v \div V/1\text{-}S_B$ (or $v \div V$) a good rule to follow (when proper allowances have been made for the Service Factor see Part 1) after choosing the value of $v \div V/1\text{-}S_B$ is to take a value of Z_g about 85 per cent of the abscissa value of the cavitation curve on Chart 9C where its ordinate value is $v \div V/1\text{-}S_B$. This will give a margin of about 15 per cent from thrust cavitation.

If the propeller is to be designed for a given Rpm. and power under trial trip conditions, the margin from thrust cavitation should be at least equal to the sum of the percentage increase in resistance under service conditions over that shown by tank test and the desired margin from thrust cavitation under service conditions. For example:

Desired margin from thrust cavitation under service conditions = 15 per cent.

Service Factory = 1.20 or an increase in resistance in service over tank test of 20 per cent.

Then the margin from thrust cavitation under trial trip conditions should be 15 + 20 = 35 per cent.

The margin from thrust cavitation is more important than that from tip speed cavitation, especially if the vessel is to be operated most of the time at lower powers than that for which the propeller is designed, as the latter (tip speed cavitation) will exist only at the higher powers while the former may exist over a large range when the effective horsepower varies approximately as the cube of the speed.

If the calculation is made using the maximum power, the margin from tip speed cavitation need not be more than 3 or 4 per cent. If the wheel is designed for normal power (and the maximum power is 10 per cent greater), the margin should be approximately 6 to 7 per cent.

In some cases, such as naval vessels which operate most of the time at powers considerably below the maximum, the propellers are often designed to be slightly in tip speed cavitation when operating

at maximum power, as this reduces the projected area ratio and gives better efficiencies at the cruising speeds.

DERIVATION OF VALUES OF A, A′ AND B IN TABLE I.

For convenience in making design calculations, values of A, A′ and B, which are given in Table I, have been prepared which were derived as follows:

Let S.H.P. = basic shaft horsepower

$S.T._d$ = basic indicated thrust in lbs. per sq. inch of disk area

T.S. = basic tip speed in feet per minute

D = diameter in feet

P = pitch in feet

R = basic Rpm. = T.S. $\div$ ($\pi \times$ D)

C = 291.8 for 3-bladed propellers
= 252.4 for 4-bladed propellers

$$S.H.P. = \frac{D^2 \times S.T.D. \times P \times R}{C} \qquad I$$

$$D = TS \div (\pi \times R) \qquad II$$

Substituting equation II in equation I, we get

$$S.H.P. = \frac{TS^2 \times P \times R \times ST_d}{R^2 \times \pi^2 \times C} = \frac{TS^2 \times P \times ST_d}{R \times \pi^2 \times C} \qquad III$$

and

$$\frac{S.H.P. \times R \times C}{P} = \frac{TS^2 \times ST_d}{\pi^2} \qquad IV$$

For convenience divide both sides of equation IV by 1,000,000 and let $C' = C \div 100$ we have

$$A' = \frac{TS^2 \times ST_d}{\pi^2 \times 1{,}000{,}000} = \frac{S.H.P. \times R \times C'}{P \times 10{,}000} \qquad V$$

Multiply both sides of the equation by P.C. and let $A = A' \times$ PC we have

$$A = \frac{TS^2 \times ST_d \times PC}{\pi^2 \times 1{,}000{,}000} = \frac{S.H.P. \times P \times C' \times PC}{P \times 10{,}000} = \frac{E.H.P. \times R \times C'}{P \times 10{,}000} \qquad VI$$

Substituting in equation I $\frac{E.H.P.}{P.C.}$ for S.H.P.

we have

$$\frac{E.H.P.}{P.C.} = \frac{D^2 \times ST_d \times P \times R}{C} \qquad VII$$

from which we get

$$B = ST_d \times P.C. = \frac{E.H.P. \times C}{D^2 \times P \times R} \qquad VIII$$

As the values of T.S. and ST_d are taken from the projected area ratio of 3 blades (in both 3- and 4-bladed wheels) while the value of P.C. is taken for the total projected area ratio

$\left(\frac{4}{3} \times \frac{P.A.}{D.C.}\right.$ for four-bladed wheels $\left.\right)$ the values of A and B will not be the same for 3- and 4-bladed propellers.

PROPELLER DESIGN FORMS.

When conditions are such that a propeller of sufficient diameter can be used either Form No. 1 or Form 2 is used. When the diameter is limited and it is necessary to resort to Fan-Shaped blades, Form 3 or 4 is used.

Design Form No. 1.—This form is used when the speed e.h.p. curve and revolutions are given and it is desired to find the characteristics of the propeller and the required shaft horsepower.

Design Form No. 2.—This form is used to obtain the characteristics of the propeller and the expected speed when the e.h.p. curve, shaft horsepower of the engine or engines and Rpm. are given. In this case it is necessary to assume the actual speed (v' line 16). If this assumed speed is close to that corresponding

to the delivered effective horsepower (N × e.h.p. line 31) the diameter and projected area ratio as found can be retained and the corrected pitch obtained as shown in line 35. Should, however, the assumed speed be considerably different (especially if it is less) from that corresponding to the actual effective horsepower, new calculations should be made using as the new estimated speed (v' line 16) the speed corresponding to the actual effective horsepower (N × e.h.p. line 31) of the first calculations. This form can also be used when the e.h.p. curve is not available, but the speed of the ship, shaft horsepower and revolutions are given.

Design Form No. 3.—If the propeller is limited in diameter and it is necessary to use Fan-Shaped blades, this form is used when the speed, e.h.p. curve and revolutions are given and it is desired to find the shaft horsepower required and the characteristics of the propeller.

Design Form No. 4.—This form is used for propellers where the diameter is limited and it is necessary to resort to Fan-Shaped blades, when the e.h.p. curve, shaft horsepower and Rpm. are given and it is required to obtain the characteristics of the propeller and the expected speed. In this case, as when Design Form No. 2 is used, it is necessary to assume the actual speed (v' line 16). If this assumed speed is close to the speed corresponding to the effective horsepower (N × e.h.p. line 34) the basic diameter and projected area ratio found may be retained, the corrected pitch being obtained as shown in line 41. Should, however, the assumed speed be considerably different (especially if it is less) from that corresponding to the actual effective horsepower, the same procedure as outlined for Design Form No. 2 should be followed. This form may also be used when the e.h.p. curve is not available, but the speed of the ship, shaft horsepower and revolutions are given.

In both Design Forms No. 3 and No. 4 various ratios of basic to actual diameter ($D \div D_1$) are assumed from which the basic diameters (D line 21) are obtained. Curves for basic diameter and projected area ratio and for pitch are drawn using actual revolutions (R_d line 39) as abscissa from which the desired propeller is chosen.

PROPELLER DESIGN FORM N°1

TYPE: SOLID OR BUILT-UP APPROXIMATE PROPELLER DIAM.=
DIAM OF HUB = ; RATIO. DIAM OF HUB ÷ DIAM OF PROPELLER =
TYPE OF BLADE SECTION ; N°. OF BLADES = ; N°. OF PROPELLERS=
GIVEN:- SPEED IN KNOTS (v), e.h.p. CURVE AND ACTUAL R.P.M. (R_d)
FIND:- ACTUAL S.H.P. ($S.H.P_d$) AND PROPELLER CHARACTERISTICS

1	No. of Blades						
2							
3	N = Number of Propellers						
4	$1-S_B$ From Hull Analysis						
5	K " " "						
6	$v \div V/1-S_B$ (Assume)						
7	$v \div V = (v \div V/1-S_B) \div (1-S_B) = (6) \div (4)$						
8	Z_q (Assume)						
9	$Z = Z_q \div K = (8) \div (5)$						
10	e.h.p. ÷ E.H.P From TABLE II						
11	Y From CHART 8A						
12	Z_R From CHART 8A						
13	$R_d \div R = Y \times Z_R = (11) \times (12)$						
14	R_d Actual R.P.M. (Given)						
15	$R = R_d \div (R_d \div R) = (14) \div (13)$ = Basic R.P.M.						
16	v = Actual Speed in Knots (Given)						
17	$V = v \div (v \div V) = (16) \div (7)$ = Basic Speed						
18	$P = \frac{V \times 101.33}{R \times (1-S_B)} = \frac{(17) \times 101.33}{(15) \times (4)}$ = Pitch in Feet						
19	N x e.h.p = e.h.p. on all shafts						
20	e.h.p. = (19) ÷ (3) = e.h.p. on one shaft						
21	$E.H.P = \frac{e.h.p.}{e.h.p \div E.H.P} = \frac{(20)}{(10)} =$ Basic E.H.P on one shaft						
22	$A = \frac{E.H.P \times R \times C'}{10,000 \times P} = \frac{(21) \times (15) \times C'}{10,000 \times (18)}$						
	3 Bladed Wheels $C' = 2.918$; 4 Bladed Wheels $C' = 2.524$						
23	PA ÷ DA From TABLE I = Proj. Area Ratio of 3 Blades						
24	$\frac{2}{3}$ PA ÷ DA = $\frac{2}{3}$ x (23) = Proj. Area Ratio of 4 Blades						
25	P.C.' From TABLE I = Uncorrected Basic Prop. Coeff. *						
26A	P.C. Correction Factor for Blade Section						
26B	P.C. " " " Roughness						
26C	P.C. " " " Hub Diam. (For Built-up Wheels Only)						
27	Total " " = (26A) x (26B) x (26C)						
28	P.C. = P.C.' x Total Correction Factor = (25) x (27)						
29	$S.H.P = E.H.P \div P.C. = (21) \div (28)$ Basic S.H.P on one shaft						
30	$S.H.P_d = S.H.P \times Z_q = (29) \times (8)$ Actual S.H.P on one Shaft						
31	$N \times S.H.P_d = (3) \times (30)$ Total Actual S.H.P.						
32	T.S. ÷ π From TABLE I †						
33	$D = \frac{T.S. \div \pi}{R} = \frac{(32)}{(13)}$ = Diameter in Feet						

* For obtaining P.C.' from TABLE I use the following
For 3 bladed wheels - use PA ÷ DA. line 23
For 4 bladed wheels - use $\frac{2}{3}$ PA ÷ DA line 24

† Use PA ÷ DA. (Line 23) in all cases (3 & 4 bladed wheels) for obtaining values of T.S. ÷ π from TABLE I

PROPELLER DESIGN FORM N°2

TYPE-SOLID or BUILT-UP APPROXIMATE PROPELLER DIAM.=
DIAM. of HUB= ; RATIO-DIAM. of HUB ÷ DIAM of PROPELLER =
TYPE of BLADE SECTION ; N°. of BLADES= ; N°of PROPELLERS=
GIVEN- ACTUAL S.H.P. ($S.H.P._a$), ACTUAL R.P.M. (R_a) AND e.h.p CURVE
FIND - SPEED in KNOTS (V) AND PROPELLER CHARACTERISTICS

1	N°. of Blades					
2						
3	N = Number of Propellers					
4	$1-S_B$ From Hull Analysis					
5	K " " "					
6	$v \div V/1-S_B$ (Assume)					
7	$v \div V = (v \div V/1-S_B) \div (1-S_B) = (6) \div (4)$					
8	Z_q (Assume)					
9	$Z = Z_q \div K = (8) \div (5)$					
10	e.h.p ÷ E.H.P. From TABLE II					
11	Y From CHART 8A					
12	Z_R " " 8A					
13	$R_d \div R = Y \times Z_R = (11) \times (12)$					
14	R_d Actual R.P.M. (Given)					
15	$R = R_d \div (R_d \div R) = (14) \div (13) =$ Basic R.P.M.					
16	V' = Estimated Actual Speed in Knots					
17	$V = v' \div (v \div V) = (16) \div (7) =$ Basic Speed					
18	$P' = \frac{V \times 101.33}{R \times (1-S_B)} = \frac{(17) \times 101.33}{(15) \times (4)} =$ Pitch in Feet					
19	$N \times S.H.P_a$ = Total Actual S.H.P on all shafts (Given)					
20	$S.H.P_a = (19) \div (3) =$ Actual S.H.P on one shaft					
21	$S.H.P = S.H.P_a \div Z_q = (20) \div (8) =$ Basic S.H.P on one shaft					
22	$A' = \frac{S.H.P \times R \times C'}{10{,}000 \times P'} = \frac{(21) \times (15) \times C'}{10{,}000 \times (18)}$					
	3 Bladed Wheels $C' = 2.918$; 4 Bladed Wheels $C' = 2.524$					
23	P.A÷D.A. From TABLE I = Prop. Area Ratio of 3 Blades					
24	$\frac{4}{3}$ P.A÷D.A = $\frac{4}{3} \times (23)$ = Prop. Area Ratio of 4 Blades					
25	P.C' From TABLE I = Uncorrected Basic Prop. Coeff *					
26A	P.C. Correction Factor for Blade Section					
26B	P.C. " " " Roughness					
26C	P.C. " " " Hub Diam (For Built Up Wheels only)					
27	Total " " = (26A) x (26B) x (26C)					
28	P.C. = P.C.' x Total Correction Factor = (25) x (27)					
29	E.H.P = S.H.P x P.C. = (21) x (28) Basic E.H.P on one shaft					
30	e.h.p = E.H.P x (e.h.p ÷ E.H.P) = (29) x (10) Actual e.h.p on one Shaft					
31	N x e.h.p = (3) x (30) = Total Actual e.h.p on all shafts					
32	T.S÷π From TABLE I †					
33	$D = (T.S \div \pi) \div R = (32) \div (15) =$ Diam. in Feet					
34	V' = Speed from e.h.p. Curve corresponding to N x e.h.p. Line 31 = Correct Speed in Knots					
35	$P = P' \times V \div V' = (18) \times (34) \div (16)$					

* For obtaining P.C.' from TABLE I use the following
For 3 bladed wheels - use P.A÷D.A (line 23)
For 4 bladed wheels - use $\frac{4}{3}$ P.A÷D.A (line 24)

† Use P.A÷D.A (line 23) in all cases (3 & 4 bladed wheels) for obtaining values of T.S÷π from TABLE I

PROPELLER DESIGN FORM N° 3
PROPELLERS OF LIMITED DIAMETER

TYPE SOLID OR BUILT-UP MAXIMUM DIAM. OF PROPELLER =
DIAM. OF HUB = ; RATIO DIAM. OF HUB ÷ DIAM. OF PROPELLER =
TYPE OF BLADE SECTION ; N°. OF BLADES = ; N° OF PROPELLERS =
GIVEN – SPEED IN KNOTS (v), e.h.p. CURVE AN ACTUAL R.P.M (R_a)
FIND – ACTUAL S.H.P. ($S.H.P_a$) AND PROPELLER CHARACTERISTICS

1	D_1 = Actual Diam. of Propeller in Feet					
2	$D \div D_1$ = Ratio Basic Diam ÷ Actual Diam.					
3	$\sqrt{D} \div D_1$					
4	$\sqrt[3]{D} \div D_1$					
5	N = Number of Propellers					
6	$1-S_B$ From Hull Analysis					
7	K " " "					
8	$v \div V/(1-S_B)$ (Assume)					
9	$v \div V = (v \div V/(1-S_B)) \div (1-S_B)$ (8) ÷ (6)					
10	Z_q (Assume)					
11	$Z_q \div K$ = (10) ÷ (7)					
12	e.h.p. ÷ E.H.P From TABLE II.					
13	Y From CHART ∅ A ($v \div V$ line 9 as abscissa)					
14	Z_R " " ∅ A (Z_q " 10 " ")					
15	$R_a \div R$ = Y x Z_R = (13) x (14)					
16	V = Actual Speed in Knots					
17	$V = v \div (v \div V)$ = (16) ÷ (9)					
18	Ntl. h.p. = Total Actual e.h.p on all shafts from e.h.p. Curve					
19	e.h.p = (18) ÷ (5) = Actual e.h.p. on one shaft					
20	E.H.P = e.h.p ÷ (e.h.p ÷ E.H.P) = (19) ÷ (12) = Basic E.H.P on one shaft					
21	$D = D_1 \times (D \div D_1)$ = (1) x (2) = Basic Diam. in Feet					
22	D^2					
23	$P_1 R = (V \times 101.33) \div (1-S_B)$ = (17) x 101.33 ÷ (6)					
24	$P_1 R \times D^2$ = (23) x (22)					
25	E.H.P x C = (20) x C 3 Bladed wheels C = 291.8 ; 4 Bladed Wheels C = 252.4					
26	$B = (E.H.P \times C) \div (P_1 R \times D^2)$ = (25) ÷ (24)					
27	P.A ÷ D.A. From TABLE I = Proj. Area Ratio of 3 Blades					
28	$\frac{4}{3}$ P.A ÷ D.A = $\frac{4}{3}$ x (27) " " " " " 4 "					
29	P.C' From TABLE I *					
30A	P.C. Correction Factor for Blade Section					
30B	P.C. " " " Roughness					
30C	P.C. " " " Hub Diam. Built-up wheels only					
31	Total " " = (30A) x (30B) x (30C) ÷ [(3) or (4)]					
32	P.C = P.C' x Total Correction Factor = (29) x (31)					
33	$S.H.P = E.H.P \div P.C$ = (20) ÷ (32) = Basic S.H.P on one shaft					
34	$S.H.P_a = S.H.P \times Z_q$ = (33) x (10) = Actual " " " "					
35	$Ntl. S.H.P_a$ = (5) x (34) = Total Actual S.H.P on all shafts					
36	T.S ÷ B From TABLE I +					
37	R = (T.S ÷ B) ÷ D = (36) ÷ (21) = Basic R.P.M.					
38	P = (P x R) ÷ R = (23) ÷ (37) = Pitch in Feet					
39	$R_a = R \times (R_a \div R) \times \sqrt{D \div D_1}$ = (37) x (15) x (3) = Actual R.P.M.					

* For obtaining P.C' from TABLE I use the following
For 3 bladed wheels use P.A. ÷ D.A. Line 27
For 4 bladed wheels use $\frac{4}{3}$ P.A ÷ D.A. Line 28

\+ Use P.A ÷ D.A (Line 27) in all cases (3 & 4 bladed wheels) for obtaining value of T.S ÷ B from TABLE I

PROPELLER DESIGN FORM N° 4
PROPELLERS OF LIMITED DIAMETER

TYPE SOLID OR BUILT-UP ; MAXIMUM DIAM. OF PROPELLER=
DIAM. OF HUB= ; RATIO DIAM. OF HUB ÷ DIAM. OF PROPELLER=
TYPE OF BLADE SECTION ; N°. OF BLADES= ; N°. of PROPELLERS=

GIVEN — ACTUAL S.H.P ($S.H.P_A$), ACTUAL R.P.M. (R_A) AND e.h.p. CURVE.
FIND — SPEED IN KNOTS AND PROPELLER CHARACTERISTICS

1	D_1 = Actual Diam. of Propeller in Feet						
2	$D \div D_1$ = Ratio Basic Diam ÷ Actual Diam.						
3	$V_D \div D_1$						
4	$\sqrt[3]{VD \div D_1}$						
5	N = Number of Propellers.						
6	$1-S_B$ From Hull Analysis.						
7	K " " "						
8	$V' \div V/1-S_B$ (Assume)						
9	$V' \div V$ = $(V \div V/1-S_B) \div (1-S_B)$ = (8) ÷ (6)						
10	Z_Q (Assume)						
11	$Z = Z_Q \div K$ = (10) ÷ (7)						
12	E.h.p. ÷ E.H.P From TABLE II						
13	Y From CHART 9A						
14	Z_R " " 8A						
17	$R_A \div R$ = Y × Z_R = (13) × (14)						
16	V' = Estimated Actual Speed in Knots						
17	$V = V' \div (V' \div V)$ = (16) ÷ (9)						
18	N × S.H.P_A = Total Actual S.H.P. on all shaft						
19	S.H.P_A = (18) ÷ (5) = Actual S.H.P. on one shaft						
20	S.H.P. = S.H.$P_A \div Z_Q$ = (19) ÷ (10) = Basic S.H.P on one shaft						
21	$D = D_1 \times (D \div D_1)$ = (1) × (2) = Basic Diam. in Feet						
22	D^5						
23	S.H.P × (1-S_B) × C = (20) × (6) × C						
	3 Bladed wheels C = 241.6 ; 4 Bladed wheels C = 252.4						
24	V × D^5 × 101.33 = (17) × (22) × 101.33						
26	$S.T_A$ = [S.H.P × (1-S_B) × C] ÷ (V × D^5 × 101.33) = (23) ÷ (24)						
26	P.A ÷ D.A. From TABLE I = Proj. Area Ratio of 3 Blades						
27	$^4/_3$ P.A ÷ D.A = $^4/_3$ × (26) " " " " " 4 "						
28	P.C' From TABLE I *						
28A	P.C. Correction Factor for Blade Section						
28B	P.C. " " " Roughness						
28C	P.C. " " " Hub Diam (Built-up wheels only)						
30	Total " " = (28A) + (28B) + (28C) ÷ [(3) or (4)]						
31	P.C. = P.C' × Total Correction Factor = (28) × (30)						
32	E.H.P = S.H.P × P.C. = (20) × (31) = Basic E.H.P on one shaft.						
33	e.h.p. = E.H.P_A = (e.h.p ÷ E.H.P) × (32) = Actual e.h.p on one shaft						
34	N × e.h.p = (5) × (33) = Total Actual e.h.p. on all Shafts.						
35	T.S ÷ π From TABLE I +						
36	R = (T.S ÷ π) ÷ D = (35) ÷ (21)						
37	(V × 101.33) ÷ (1-S_B) = [(17) × 101.33] ÷ (6)						
38	P' = (V × 101.33) ÷ [(1-S_B) × R] = (37) ÷ (36)						
39	$R_A = R \times (R_A \div R) \times V_D \div D_1$ = (36) × (15) × (3)						
40	V = Speed in Knots from e.h.p. Curve corresponding To N × e.h.p (Line 34) = Correct Speed						
41	P = P' × V ÷ V' = (38) × (40) ÷ (16)						

* For obtaining P.C' from TABLE I use the following
For 3 bladed wheels use P.A ÷ D.A Line 26
For 4 bladed wheels use $^4/_3$ P.A ÷ D.A Line 27

† Use P.A ÷ D.A. (Line 26) in all cases (3 & 4 bladed wheels) for obtaining value of T.S ÷ π from TABLE I

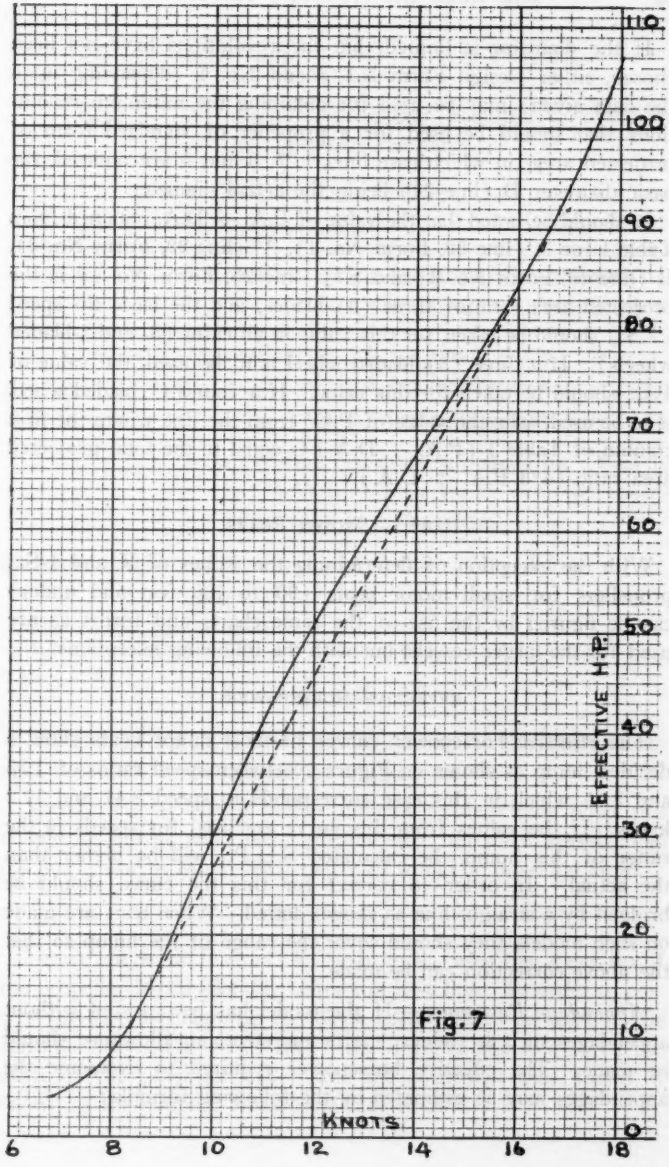

110
100
90
80
70
60
50
40
30
20
10
0
EFFECTIVE H.P.
6
8
10
12
14
16
18
KNOTS

Fig. 7

If the diameter is limited, but the revolutions have not been chosen, either Design Form No. 3 and No. 4 (depending upon the data given) may be used for obtaining the minimum revolutions that should be used for a propeller of standard form of projected area, in which case lines 1, 2, 3 and 4 are omitted, the basic diameter D (line 21) being the actual diameter.

It should be noted that the value of P.A. ÷ D.A. obtained from Table I for A (line 22, Form No. 1), A′ (line 22, Form No. 2), B (line 26, Form No. 3) and ST_d (line 25, Form No. 4) is the projected area ratio of three (3) blades, and the basic tip speed (T.S.) should be taken for this value in all cases (3- and 4-bladed wheels). If a three (3) bladed wheel is to be used, the value of P.C.′ should be taken for this value. If a four (4) bladed wheel is to be used, take the value of P.C.′ from the line where the first column of Table I (P.A. ÷ D.A.) is equal to the total projected area ratio (4/3 P.A. ÷ D.A.).

Part 7—Motor Boats.

With the exception of determining the values of K and $1\text{-}S_B$, propellers for small motor boats (90 to 100 feet and under) can be figured by the use of the same charts and forms as are used for the larger vessels, but with the following exceptions.

EFFECTIVE HORSEPOWER.

The effective horsepower curves of most motor boats show a decided hump as shown on Figure 7 between speed ratios of 1.35 and 2.75 which in this case corresponds to speed 8.47 and 17.2 knots. If the values from this curve are used for speeds in the range of this hump, the calculated $S.H.P._d$ will be higher than the actual. In order to correct for this the curve should be bridged by a straight line as shown dotted. When tests are made on such models they should cover the range of the hump so that the above correction can be made.

Appendage Resistance.—If the model has been tested without appendages such as rudder, shafts and struts an allowance should be made. The effective horsepower required to overcome the appendages may be estimated by the following formula:

$$e.h.p._a = .00307 \times \left(\frac{L}{10}\right)^3 \times r \times v \times C_1 \times C_2$$

$e.h.p._a$ = effective horsepower required to overcome the appendage resistance

L = length L.W.L. in feet

v = speed in knots

C_1 = constant = 1.0 for struts with one arm
= 1.4 for struts with two arms

C_2 = constant = 1.0 for single screw
= 1.8 for twin screws
= 2.6 for triple screws

r = appendage resistance in pounds for a boat 10 feet L.W.L., which varies with the speed-length ratio as given below:

$v \div \sqrt{L.W.L.}$ =	0	.5	1.0	1.5	2.0	2.5
r =	0	.17	.37	.60	.90	1.28
$v \div \sqrt{L.W.L.}$ =	3.0	4.0	5.0	6.0		
r =	1.7	2.57	3.45	4.20		

The above formula is based on the assumption that the appendages resistance follow the law of comparison.

Service Factor.—It is rather difficult to determine what this should be, but as wind has a greater effect on small vessels than the larger one, it would seem that 1.20 would be none too large.

THE HULL.

Power Augment Factor "K".—In most cases the lower tip of the propeller is considerably below the base line. In order to correct for this in obtaining the block coefficient to be used in the formula (B ÷ L) ÷ (1-B.C.), the draft is assumed to be the draft of the propeller (H″), and the coefficient thus found is known as the nominal block coefficient (N.B.C.).

Chart 4F shows the value of K for various values of (B ÷ L) ÷ (1-N.B.C.). 1-S_B. Analyses of several boats show a very small variation in this value, the average being .78 which can be taken in all cases.

Tip Clearance.—In order to reduce the chances of undue noise and vibration, the clearance between the hull and the tips of the propeller should, when possible, be not less than eight per cent of the square root of the load water line length (T.C. = .0 8 × $\sqrt{\text{L.W.L.}}$).

CAVITATION.

Tip Speed Cavitation.—The only data available was on a boat which was not run over a measured mile. This showed that tip speed cavitation commences at approximately the same revolutions as for larger vessels (See Part 5).

Thrust Cavitation.—As the value of 1-S_P, is less than .80, propellers on these boats enter thrust cavitation when the performance plots below Curve 2 of Chart 90. The same rules for large vessels held here, the actual shaft horsepower being obtained in the same manner. If the performance plots between Curves 1 and 2 there is (as in larger vessels) no correction to be applied when calculating revolutions, but if the performance plots below Curve 1, the correction factor M from Chart 8C should be used, using Curve 1 for obtaining the value of $v_e \div V/1\text{-}S_B$. The value M, however, is never greater than 1.05.

FAN-SHAPED BLADES.

When fan-shaped blades are used and the propellers are not operating in thrust cavitation, the rules for larger vessels apply. If, however, thrust cavitation exists, the value $\sqrt{D \div D_1}$ is not (for some unknown reason except that analyses show this to be the case) used in obtaining the basic revolutions (R).

APPROXIMATE DIAMETER OF PROPELLER.

In making the first preliminary design calculation, when the position of the shaft has not been determined, it is necessary to know the approximate diameter of the propeller so its location

and the nominal block coefficient (N.B.C.) can be estimated. In order to do this, the following formula may be used:

$$\text{Diameter in feet} = 2.15 \times \left(\frac{1000 \times \sqrt[3]{\text{S.H.P.}}}{\text{Rpm.} \times \sqrt{v}} \right)^{.5}$$

S.H.P. = shaft horsepower on one shaft

Rpm. = revolutions per minute

v = speed in knots

NOTES.

INDEX TO NOTES.

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FREQUENCY.

Dr. Simon Ramo of General Electric's Electronic Laboratory discusses the basic concepts of current flow along conductors and in tubes, circuits, radiation, etc., for electromagnetic waves in the range of frequencies described in billions of cycles per second. Dr. Ramo's article is reprinted from General Electric Review for October, 1942.

Electrical engineers, who work exclusively at the power frequencies, often believe that the radio engineer, who works in the broadcast-frequency range, never talks the "same language." The thought is, of course, that the characteristics of electricity change sufficiently with frequency that not alone do the applications vary enormously between the few cycles per second of power and the 1,000,000 cycles per second of radio broadcasting, but the electrical concepts, the physical pictures in the mind of the engineer also are very much different. If between a few cycles per second and 1,000,000 cycles per second there are already appreciable differences in the way in which engineers view the most basic concepts of electricity, it is easy to imagine that electricity will act so differently at an alternation rate of one billion cycles per second that further translation will be required if engineers working in the three frequency ranges thus mentioned are to converse.

In this article an attempt will be made to discuss some of the characteristics which electricity possesses, when the frequency of alternation reaches the range of billions of cycles per second, in language that is more or less universal and independent of frequency. The discussion will be concerned with the physical pictures which engineers working in this field are coming to have of such basic concepts as current flow along conductors and in tubes, circuits, radation, etc. Before discussing how the language of microwave engineers, radio-broadcast engineers, and power engineers may be expected to differ, let us see briefly why, for certain basic reasons, the language of all who work with electricity should be the same.

A simplified reproduction of one of the most descriptive diagrams the physicists have yet given us is shown in Figure 1. It represents a plot of the

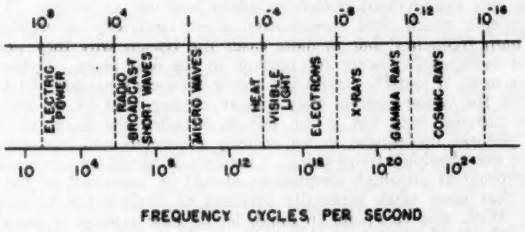


FIGURE 1.—THE ELECTROMAGNETIC SPECTRUM IN TERMS OF METERS AND CYCLES PER SECOND.

spectrum of electromagnetic phenomena, frequency and wavelength of electromagnetic radiation—from the power frequencies to the radio bands for ordinary broadcast radio, FM, television; past the ultra-highs, out of the region we call radio waves, and into what we call heat waves or rays; then light

rays, visible and ultraviolet, and off into electron beams or cathode rays, X-rays, and cosmic rays. All are electromagnetic phenomena—cousins, differing in at least one basic way; frequency or wavelength. Frequencies may vary from a few to well over a few trillion alternations per second, wavelengths from over a billion meters to a billionth of a meter.

The portion of the spectrum with which we are presently concerned is in the range of wavelength described in centimeters or in the range of frequencies described in billions of cycles per second—a region which (except for Hertz' brilliant impudence in producing sparks near there as the first experiment in radio long before the intervening region had been gone over at all) we have reached by advancing steadily upward in frequency from the longer wavelengths at the left end of the diagram in Figure 1.

Notice how far on the spectrum this centimeter-wave region is from the power frequencies, and how appreciably close it is to the heat region and even the light region. In fact the distance from the centimeter-wave region to the ordinary radio-broadcast band and to the heat and light waves are the same order of magnitude. As we look at this diagram, we cannot help wondering how far we can continue to go towards higher frequencies before we cease talking about those ultrahigh frequencies as radio waves and begin to call them heat or light waves—or better yet perhaps some new name is needed to show that these microwaves are separated from radio-broadcast and heat waves, just as heat is separated from light. Also it is to be expected, is it not, that if we are going to borrow concepts to help us understand and describe these centimeter waves, we should end up by borrowing from the waves that are shorter, as well as those that are longer.

Suppose we had previously worked with light and heat waves exclusively and gradually found means to make those waves longer until we found ourselves, let us imagine, into the really long wavelengths at the extreme left in Figure 1. In light one speaks about the index of refraction, prisms, lenses, and in heat one thinks about the temperature of the source, blackbody radiation, and so on. Suppose we had to wait to have it occur to us that such things as motors and power lines and broadcasting stations might be practical realizations, with our thinking governed entirely by concepts like focal lengths, virtual images, probably some low-frequency extension of Plank's radiation law, and a definition of entropy.

Actually the situation is not so radically different in the centimeter-wave region as this exaggerated reasoning might lead one to believe. There are many concepts which need modification when electricity alternates at extremely high frequency, but in most cases the reason why they need modification is because they were too narrow in the first place. If the broader concept is used, it usually covers the whole frequency range. At the lower frequencies the broad concept may appear clumsy, and so we are satisfied with the narrow one; but if we fail to broaden the base, we find our physical pictures inadequate, if not entirely erroneous and misleading when applied to the ultrahigh frequencies. Certainly it would be unwise to expect that everything at ultrahigh frequencies should be explained on the basis of concepts that were often especially invented to explain low-frequency phenomena. With this viewpoint in mind, let us now attempt a description of the presently developing physical pictures of electrical concepts in the microwave region.

Current Flow in Conductors.

The picture which an electrical engineer uses at the lower frequencies for current flow in a conductor is an exceedingly simple one, and it is almost as simple at the higher frequencies. At low frequencies, he thinks of the current as a flow contained in the conductor. The manner in which the cur-

rent distributes itself depends upon frequency. If the frequency is low, then the current distributes itself uniformly in a conductor, as shown in Figure 2, just as direct current would; and it is well known that as the frequency increases, there is a tendency for the current flowing in a solid conductor to move toward the surface. The "skin effect" increases in its importance with increasing frequency, and the frequency does not have to become very high before the proper picture of current flow must consider skin effect; certainly every electrical engineer who works with radio frequencies includes this effect 100 per cent of the time in his mental picture of electric-current flow in conductors, if not in his computations.

FIGURE 2.—THE CURRENT FLOWING IN A SOLID CONDUCTOR TENDS TO MOVE TOWARD THE SURFACE AS THE FREQUENCY IS INCREASED.

At frequencies of the order of one billion cycles per second, the current comes so close to flowing entirely on the surface of conductors that if you penetrate into a copper conductor a few thousandths of an inch, then there is hardly any current left worth talking about. In other words, skin effect reaches its ultimate and electric currents become just a surface phenomenon. Electric currents then do not flow in conductors in the microwave region; they flow on conductors for all practical purposes.

Now this has a very important effect upon the engineer's thinking. You see, almost the first thing you want to know about centimeter waves is where they are, where is the energy being stored, and toward where is the power being guided. If nothing really goes on inside of conductors, if only conductor surfaces take part in the action, then the conductors become simply boundaries, enclosing regions in which the centimeter waves really do their propagating and existing. It will readily be understood by the power engineer then, why the microwave engineer substitutes a good deal of the time in his thinking with pictures of electric and magnetic fields in place of working entirely with current and charges or voltages of the system.

This doesn't mean at all that the concepts of *current* and *charge* and *voltage* have become obsolete. A better way to say it is that these concepts share the limelight with *fields* in situations where previously the field concepts had been in the background. That sharing often brings a broader, rather than a narrower appreciation of the current and voltage concepts.

Of course, at any frequency, when you commence to deal with circuit impedances, inductances, capacitances, somewhere back in the analysis you or someone else has had to pass through a consideration of the electric- and magnetic-field distribution. That is, our familiar picture of the relations between current, voltage, and charges of electrical systems ultimately depend upon linkages between those systems that come about because of their fields. In our usual physical picture the electric and magnetic fields are "feelers" which emanate from the centers of electromagnetic effects and are useful in accounting for the interaction between different conducting systems. But the center of the problem at the power frequencies is in the conductors and the current flow along those conductors. Two examples of simple common

cases in the microwave region illustrate how the center of the problem moves away from the voltages and currents and charges to the region surrounded by charges and current in which electric and magnetic fields exist.

In Figure 3 we see a system that might be used for transmitting electromagnetic energy in the microwave region, a long cylindrical conducting tube with a source of centimeter waves near one end. A small spherical probe is charged by the high-frequency generator so that lines of electric flux from that probe end on the cylinder's walls, and if the frequency is high enough, electromagnetic fields will propagate down the tube. We shall go into this example a bit more later, under the heading of transmission of microwaves, but for the time being we note that what goes on in the tube may, of course, be studied with the spotlight on the current flow and the charges on the inner-surface of the cylinder. Electric currents flow, however, only on that boundary, and it is difficult to avoid looking upon the situation pictured as one in which the center of the problem is no longer in the metal, but in the space surrounded by the metal. So we look upon the cylinder as a "wave guide."

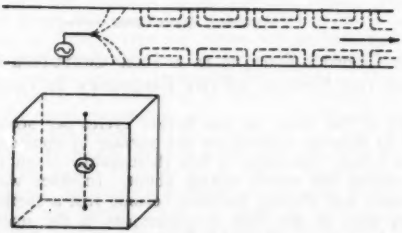


FIGURE 3.—(TOP) IF THE FREQUENCY IS HIGH ENOUGH, ELECTROMAGNETIC FIELDS WILL PROPAGATE DOWN A HOLLOW CONDUCTING TUBE. (BOTTOM) IN SOME RESPECTS THIS HOLLOW BOX IS TYPICAL OF ULTRAHIGH-FREQUENCY RESONANT CIRCUITS.

The second diagram in Figure 3 shows a hollow box which is in some ways typical of resonant circuits at ultrahigh frequencies. Again, this example will be studied more carefully under the heading of microwave circuits, but at this time we assume that there is a source of centimeter-wave energy inside the box and that as a result there is current flow on the inside surface. The top and bottom of the box become oppositely charged, and currents connecting these charged top and bottom plates flow up and down the walls of the box between those condenser plates. But again, because no effect exists outside the box, due to the negligible penetration of current at these frequencies, and because the box walls are boundaries of the problem, the focal point of the problem appears to a great extent to be the space enclosed by the box, rather than the conductor itself.

In a much broader sense than that to which engineers who have not worked with centimeter waves will have become accustomed, current flow becomes a boundary condition—not the central core in the picture. This, you see, begins to make electric effects in the centimeter-wave region ally closely with light waves which we usually consider as passing through a medium with the boundaries acting as absorbers or reflectors, but nevertheless boundaries only. We ordinarily think of light as a phenomenon which takes place in a medium which will transmit it—not as something that takes place along mirrors or along other boundary surfaces.

We shall come back to this picture of centimeter-wave current flow along conductors later when we consider circuits and transmission lines. For the present it will be sufficient to give free reign to the idea that at these extremely high frequencies there is practically no such thing as current flow in conductors. Charges and current sit and flow on the conductor surfaces.

Current Flow in Vacuum Tubes.

It was stated earlier that this article is to be about basic ideas underlying the physical pictures which engineers have of microwave electricity. The reader is justified in asking (it having been assumed that he is not a microwave engineer) why current flow in a vacuum tube, which is presumably a "device," should be introduced here as a fundamental concept. The answer brings out a characteristic of microwave electricity of extreme importance.

At the lower frequencies the vacuum tube is perhaps best described as a device. It is something which can be inserted into a circuit and made to perform many unusual jobs not possible with simple circuit elements such as R, L and C.

Now the electron tube is the machinery of the centimeter-wave engineer even more so than it is to the radio-broadcast engineer, and tubes and circuits are so closely interrelated that any concept of current flow is poor unless it correctly pictures microwave current flow from conductors into electron beams and back to conductors again. A large portion of the time, the current of the system is in "raw" electrons going through a vacuum rather than in current flow along conductors. So we can say that we are not discussing the basic characteristics of devices; rather, we are considering the other basic type of current flow: free electrons in vacuum.

A convenient way to study some basic notions which the centimeter-wave engineer has come to associate with current flow in vacuum tubes is to consider the operation of a simple triode vacuum tube at low frequencies. We shall try to see where our usual notions break down when the frequency becomes high. Briefly, if the reader will refer to Figure 4, the usual ex-

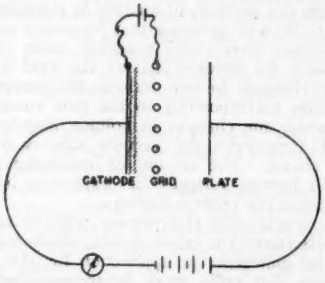


Figure 4.—A Simple Triode Vacuum-Tube Circuit.

planation of its operation is about as follows: The cathode, we are taught, emits an abundance of electrons, and these would normally flow hurriedly to the plate, which is maintained at some higher positive voltage with respect to the cathode, were it not for the effect of the space charge of the electrons themselves; that is, the electrons in filling the space in the region between cathode and grid exercise a repulsion effect on the electrons that have just

been emitted and are anxious to start toward the plate. As a result, only a certain definite amount of electrons, depending upon the conditions of balance, will be allowed to migrate to the plate. The first part of the picture, then, is that current flows between cathode and plate and back around through the external circuit to form a closed path. The greater the number of charges (electrons) per second reaching the plate per unit time, the greater the number of amperes the ammeter in the circuit indicates.

The grid is cleverly interposed in the space-charge region between plate and cathode, and being relatively close to the cathode it exerts a more powerful control effect on the electrons near the cathode than does the plate. A change in grid voltage results in a change in the space-charge condition near the cathode and consequently a change in plate current—even if the plate voltage is held constant. The tube manufacturer presents us with a neat set of curves giving the relation between the various currents and voltage. If, as shown in Figure 5, we wish to design a common resistance-loaded amplifier, we look at these curves and find what the current flow through that resistor will be. Consequently the voltage drop across it, for a given amount of input signal, and the voltage amplification are determined.

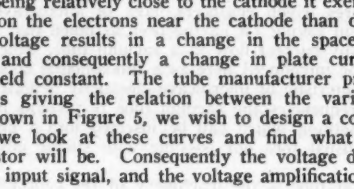


FIGURE 5.—CIRCUIT OF A COMMON RESISTANCE-LOADED AMPLIFIER.

Throughout the explanation no word was mentioned of the time it takes for the grid to exert its effect on the space-charge region, nor the time it takes electrons to dash from one position to another in compliance with the orders of the applied signal. It was assumed that for every set of values of plate voltage and grid voltage, there exists a certain value of plate current, and moreover it was taken for granted that if the grid voltage or the plate voltage or both are changed to new values, the current will immediately change to a new value, corresponding to the new voltages, without regard to the speed with which the changes in voltage may have been made. In other words, at low frequencies the vacuum tube is simply an impedance introduced into the circuit. The amount of impedance which it presents is determined by the d-c biasing voltages that happen to be on the electrodes; if those voltages change, the current changes.

Now we know, of course, that this picture, with its assumption of instantaneous motion of electrons (in other words, short transit time) is quite valid, and leads to no difficulties in application for the frequency range in which most of power and radio work is accomplished. We know also, from a good deal of recent literature, that transit time of electrons in vacuum tubes has not been overlooked, and a number of new tubes applying particularly to the centimeter-wave region have been described, in which the fact that the electron takes an appreciable part of a cycle or actually many cycles of radio frequency to travel between electrodes is of prime importance in the operation of the device. But suppose that we did not know this and we were determining for the first time how a simple triode operates, bearing in mind that the frequencies might really become high. We would again describe the conditions of space-charge limitation of current, and come to

the conclusion that for a given set of static voltages a given current should flow to the plate. Next, let us add a rapidly oscillating voltage between the grid and cathode. Being fortunately ignorant, it will probably not occur to us that the space charge could jump instantaneously to an oscillating condition in exact step with the grid voltage, nor that the plate current likewise will be caused to vary periodically in synchronism with the grid voltage in such a way that the instantaneous value of plate current will always be related to the instantaneous grid voltage as though both were static.

Instead, unsophisticated as we are, we should doubtless argue as follows: The application of the oscillating voltage on the grid will result in a periodic attraction and repulsion of electrons toward the grid. The result will be that the space-charge electrons near the cathode will commence to move under the influence of this periodic force. For example, we might expect that as the grid voltage approaches its highest positive value, the electrons near the cathode should experience an increasing attraction toward the grid. In consequence of this attraction they would start to move toward the grid. However, the applied frequency may be such that when the electrons have travelled only a small part of the distance between cathode and grid, the grid potential will begin to reverse, and the space-charge electrons will then be repelled by the grid and begin to move back again.

The plate in the meantime remains quite puzzled as to what is expected of its current. Had the grid behaved properly and removed a good measure of the space charge from in front of the cathode on each positive part of the cycle, we would have expected to find an increase in plate current periodically. But as the situation was described, with the grid wavering in its attitude so that the space charge and the electrons contemplating leaving the cathode region had also to dilly-dally, it becomes a matter of some difficulty to determine just what effect, if any, the plate will receive from such action by the grid.

If the current flowing to an electrode in a vacuum tube is viewed as resulting from the collection of electrons at the electrode, then in the case described the plate will receive no alternating current whatsoever. Suppose we go back and lower the frequency just a little—enough so that before the signal voltage on the grid changes its mind, a substantial number of electrons will have passed through the grid; when the grid reverses potential those electrons will flow to the plate presumably resulting in some plate current.

The implication of all this is that there is a sudden point in increasing frequency for a given amplitude of signal at which plate current suddenly ceases to flow.

All of these difficulties can be resolved at once, if we reject as fundamental the concept that current flow to an electrode in a vacuum tube is a result of the instantaneous collection of electrons.

That concept may serve us well at times, but in general, to play safe, it is best to use the more fundamental picture that current flow in the external circuit that connects electrodes of a vacumm tube is due to the changing of those charges on the electrodes which were induced by the moving electrons in the space between electrodes. That this is so can readily be appreciated by reference to the diagrams in Figure 6.

Figure 6 pictures an electron—a single charged body—passing between two electrodes in a vacuum tube which are connected externally through an ammeter. We see the electron first near the electrode at the left with lines of electric field flux from it falling upon the other two electrodes, and ending there on positive charges which will be induced on the plates to match the negative charge of the electron. The ratio in which the positive charge divides itself between the two electrodes is, of course, dependent upon the adjacency of the electron to these electrodes. At first with the electron

near to the electrode on the left, most of the induced positive charge is on that electrode, but as the electron moves, a greater percentage of that positive charge appears on the plate to the right. This means, of course, that some of the positive charges from the left electrode must be moving through the ammeter, appearing on the electrode at the right at just the correct time to receive the flux lines that have shifted over. As the electron moves between the two plates, the amount of charge on the left electrode decreases and the amount of positive charge on the electrode at the right increases. Consequently, throughout the motion, a current, which is a measure of the *rate of change of charge*, flows through the ammeter.

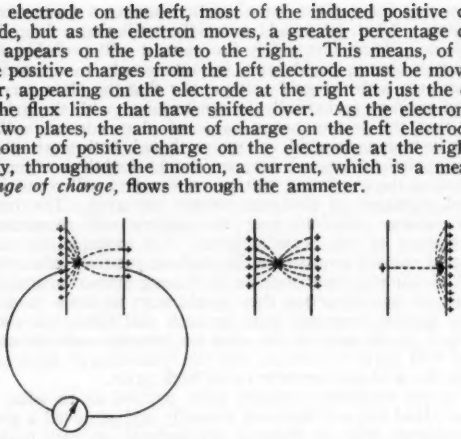


FIGURE 6.—AS AN ELECTRON MOVES BETWEEN TWO ELECTRODES IN A VACUUM TUBE, THE POSITIVE CHARGES REDISTRIBUTE THEMSELVES AS SHOWN, PASSING THROUGH THE EXTERNAL CIRCUIT.

Finally, as the electron nears the electrode at the right, all of the positive charge, or essentially all of it, now accumulates on that electrode. At the very end of the trip, when the electron finally lands at the plate, it meets the equal positive charge resting entirely on that plate (with no charge whatsoever on the opposite plate). The electron neutralizes that charge and the flow through the ammeter becomes zero.

Current flows all the time during the electron motion. Indeed, it stops only when the electron has finally arrived. From this picture we see immediately that it is not necessary that an electrode be collecting electrons in order that there be current flow. It must receive electrons if it is to pass a direct current, but instantaneous current will flow while the electron is simply approaching the plate. Had the electron turned around and gone back before it had completed all of its travel, then the instantaneous current would have reversed, but it would have been zero only at those times during the process when the electron velocity happened to be zero.

A safe and correct viewpoint is always to consider the current in an electron tube as arising from induction because of the motion of charges in the space between electrodes. When the electron is finally collected isn't the time when current flows; as a matter of fact, that is the time when current due to that electron ceases to flow.

If there is a continuous stream of electrons coming from, say, a cathode to an anode, then, as each electron moves across, it transfers the matching electric charge, present on the face of the electrodes, from the cathode to the anode through the external circuit. A continuous process, a steady flow of electrons, means then that the current flowing in the circuit is equal to the number of electrons per second arriving at the plate. In this case, the two concepts agree: current flow in a vacuum tube may be regarded as due to the instantaneous collection density of electrons to the electrode, or it may be regarded as a movement through the external circuit of the induced

charges on the electrode, occasioned by the electrons' presence and motion. Whichever way you look at it, you get the same answer. But notice that in the absence of this regularity, there is nothing in the rules that says that the number of electrons leaving the cathode at any instant must equal the number of electrons arriving at the plate at that same instant. Particularly is this so if the frequency is so high that the time taken by electrons to move across compares with the time for a complete electrical cycle.

The centimeter-wave engineer, when he thinks of current flow through an electron tube, cannot overlook the fact that the current flow is due to a motion of charges, and it is an integrated effect of all the induced current due to all the charges with which he must deal. The chief tool, the chief machine of the engineer in the centimeter-wave region, the vacuum tube, is not universally looked at as a switch or an impedance which can be varied by variation of the various biasing voltages on the electrodes. Instead the centimeter-wave engineer is concerned with electron paths, electron velocities, trans-time, induced currents, and movements of waves of space charge.

Electric Circuits.

Let us turn away now from those very important but confusing electrons and go back to more general pictures of the characteristics of centimeter waves near conductors. Our first subject under this broad heading has been classed as "circuits." Electric Circuits to the power engineer and the radio-broadcast engineer is a title that covers almost all of the fundamentals. It can certainly be considered to include all transmission lines, and possibly all electrical phenomena but radiation. There are a number of factors that one might point out immediately as changing the physical picture which an engineer has of "circuits," when the frequency goes from thousands, past millions, up to billions of cycles per second.

But all of these differences are inter-related, and one difference is the result or a cause of another difference. It will probably be best to take a simple circuit (at least, it is simple at the lower frequencies) and attempt an analysis of that circuit, adding more rigor as the frequency increases, until one by one these many differences become apparent. If we had to analyze the circuit of Figure 7 at the lower frequencies, we would probably

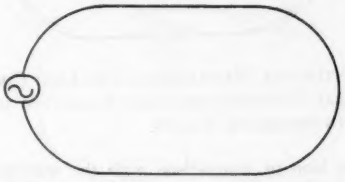


Figure 7.—A Simple Circuit Consisting of a Generator and Conducting Loop.

proceed somewhat as follows. The voltage that is applied to the loop causes some current to flow. To find out how much current flows, we would contribute a certain amount of the voltage towards overcoming ohmic losses, the IR drop, and a certain amount towards overcoming the induced electromotive force. One way to look at this, of course, is that the magnetic field is changing, and this in turn causes induced electric field at every point in the loop. The cumulative effect of that distributed electric

field is to require that a certain amount of the applied voltage be used up in overcoming it to permit current to flow.

Sometime before radio waves had been discovered, Maxwell set up a theory of electricity and magnetism, which is still tops today in the electromagnetic spectrum, that covers the radio and power frequencies and which applies to many of the basic phenomena of heat and light waves. The most startling thing about Maxwell's equations at that time, and perhaps the most important single conclusion of his applicable to the centimeter-wave region today, is that they predicted that electric and magnetic fields do not jump into existence in the space surrounding charges and currents which caused them instantaneously. Rather, the electric and magnetic fields travel away from their sources with the velocity of light. These equations gave rise to the electromagnetic theory of light and formed the first important link between light and electricity indicated on the spectrum shown in Figure 1, and it is this very basic discovery of Maxwell which yields the link that we must add to our low-frequency notions of electricity if we are to analyze properly centimeter-wave systems, such as the circuit in Figure 7. In the analysis we indicated in the last paragraph, nothing was mentioned about the time it takes for the magnetic field due to the current in one part of the loop to make itself felt at another part of the loop. It was assumed that the field travels so quickly, compared to the size of the loop, that the magnetic field due to the current is in exact step with that current.

But what do we mean when we say that the size of a loop is small? The time it takes for an electric or magnetic field to cross the loop must be compared with the time it takes for the electricity to go through an alternation. If that time becomes appreciable by comparison, then the loop is not any longer small. It is not, in other words, the absolute size of the loop

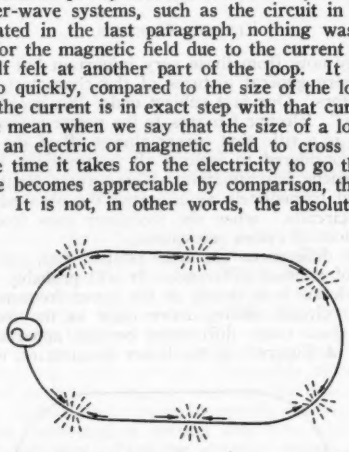


FIGURE 8.—AT CENTIMETER WAVELENGTHS THE LOOP CIRCUIT OF FIGURE 7 MAY BE SEVERAL WAVELENGTHS LONG RESULTING IN CHARGES BEING BUILT UP AT INTERMEDIATE POINTS.

but the size of the loop in comparison with the wavelength that matters. Well, wavelengths in the centimeter range will not call for very large loops before it begins to take an appreciable part of the period of a cycle for the effects of current changes in one part of the circuit to be felt in other parts.

We ordinarily think of inductance as causing a current to be 90 degrees out of phase with the voltage across it. A pure inductance, we say, takes no average power. If, however, the magnetic field takes a part of a cycle to get from one side of the circuit to another, there is going to be some delay or retardation and some change or expansion in our circuit notions. A small amount of the induced electric field will be in phase with the current in the wire. We will thus sustain a loss, not in heating up the circuit, because it had nothing to do with the ohmic resistance of the circuit, but a

loss that leaks out through the electromagnetic field. Perhaps an even greater setback is the realization that our friend, the pure inductance, seems to be capable of aggression on pure resistance. We do not have to throw out the inductance concept, but we have to broaden it a bit.

The loop of Figure 7 might easily be several wavelengths long. Then periodically around the loop we shall find that the current in one part of the circuit may be going in one direction while in another part of the circuit it is going in the opposite direction as shown in Figure 8. You may correctly conclude that when such a thing happens to current it means that charge must be piling up at intermediate points. That is, if as shown in the figure the current is flowing toward a certain point on a conductor from one direction and also toward it from the other direction, then at that instant the charge must be building up.

It might be well to draw one further conclusion at this point before we go on to develop this situation further and see more of the characteristics of centimeter waves, and that conclusion is that circuits in the usual sense in which our picture is one of a current flow, uniform in magnitude and phase, and lying entirely in the conductors all the way around—that concept of circuit is practically nonexistent in the centimeter-wave field. With the wavelength in the range of centimeters (the distance from zero to the positive maximum of current along a conductor being only a quarter of a wavelength and thus even shorter) it is very rare that circuits small enough physically to look like low-frequency circuits, can be used.

So we accept the fact that the current is not going to be uniform around the loop of any circuit whose length is at least comparable to wavelength; but this is only a beginning.

Those of you familiar with transmission-line theory will immediately recognize that it will usually be preferable, in a system of the type just described, to consider it as a transmission line rather than a single loop circuit in the first place. The length being too long for one simple circuit, we should, it seems, think of it as made up of an infinite series of little circuits. There are series-impedance effects and there must indeed be shunt-admittance effects across the loop because the charges, which we have seen must gather at the current nodes, are significant in determining the over-all performance of the system. So it would appear that the presentation in Figure 9, where

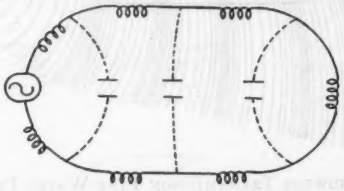


FIGURE 9.—AT ULTRAHIGH FREQUENCIES THE CIRCUIT OF FIGURE 7 WOULD APPEAR AS SHOWN HERE WITH THE COILS AND CONDENSERS REPRESENTING SERIES IMPEDANCES AND SHUNT ADMITTANCES.

the series impedances and shunt admittances are indicated by the many coils and condensers, is preferable.

The method of distributed inductance and capacitance has been demonstrated to be an effective and valuable one for many phases of the ultrahigh-frequency-circuit problem. It is extremely useful, for example, in predicting

approximate distributions of currents and voltages at various parts of the circuit. It has, however, one outstanding limitation: though you may distribute impedance and admittance at will over the circuit in an attempt to realize the proper magnitude and phase differences of the currents around the loop, you still have allowed for only one way in which energy can be lost in such a system, and that is in the I^2R loss of the coils and condensers. Unfortunately, our little loop is not an ordinary transmission line. It is not one which, for example, can be thought of as guiding energy uniformly for a distance, then depositing that energy completely into a load at the end. Nor is it one in which the energy is simply all reflected back to the source. Because of the nonuniformity of the transmission line and because of the factors which we have already discussed, perhaps Figure 10 comes closer to portraying at least the spirit of the actual situation. Here we acknowledge again that the centimeter-wave energy lies mainly in the dielectric medium around the conductor, not penetrating the conductors appreciably so that the latter serve merely as guides. We think then of the loop conductors as guiding the waves from the source along the loop to be reflected at various points of the loop back to the source, but also to be spread out over some distance and lost from the system forever.

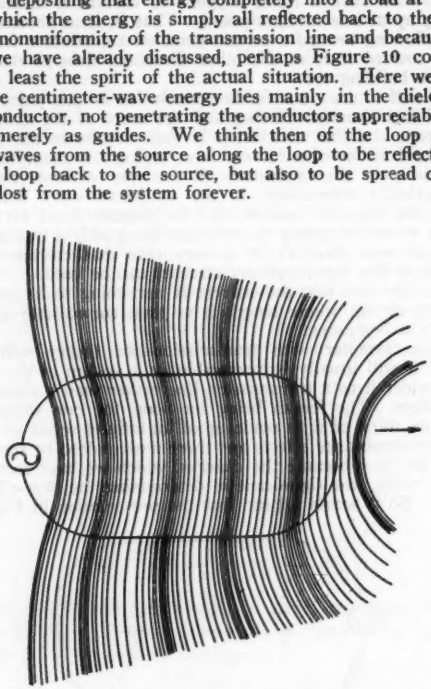


FIGURE 10.—SHOWING TRANSMISSION LINE WAVES PROGRESSING OUT FROM THE SOURCE OF THE LOOP CIRCUIT.

The writer has taken many liberties in the diagram in Figure 10 which shows the transmission line waves progressing out from the source, with an appreciable amount of energy never getting back by the large amount of reflections (which are not shown) but being lost in electromagnetic-field leakage or radiation. The distributions of the wave are intended only to convey an impression and are not based on a mathematical field plot. A good deal of the energy in the transmission-line waves will undoubtedly be reflected back to the source. Indeed, if all of the energy were so reflected

(and we are neglecting for the moment the I^2R losses in the metal of the loop itself) then the source would, of course, see nothing but pure reactance. That it does not do so ties up with our earlier conclusion that the ordinary (low-frequency defined) "inductance" is no longer loss-free in the centimeter-wave region. We see that though some energy is guided up and down the loop other energy gets away even without our attempting to make it do so. This circuit has become an antenna; it radiates power.

And now we have come upon another important property of centimeter-wave circuits. First, we have said that circuits in the usual sense hardly ever exist at these frequencies because it is so difficult to build something physically tiny enough really to be a circuit; and then we have said that, small though the circuits are (or perhaps we should say "large" though the circuits are, compared to wavelength), the radiation from those circuits, the loss of energy by electromagnetic waves which simply get up and leave, is proportionately large. A major problem of the centimeter-wave engineer in most of the systems which he designs is to keep that radiation under control. Of course, in designing radio antennas you want the radiation to be high, but even then you want it to be under your thumb. It is desired that the engineer should know where the electromagnetic energy is going, and why, and the system should be efficient. In circuit design, you rarely are pleased to lose energy by radiation any more than by I^2R losses.

The centimeter-wave engineer has, in other words, a problem in insulation. Here we see centimeter-waves acting a good deal like heat, as well as light. Unless you have completely closed structures through which the waves will not penetrate, then in all three cases you may expect to have leakage by radiation.

In the important fact that the centimeter-waves will not appreciably penetrate metal, we find indeed the answer to the question of how to design circuits at these high frequencies so that the leakage of energy by radiation will not be excessive. If you build a circuit, build it so that the current flow around that circuit is self-enclosing. The practical realization of this trend of thought is the common centimeter-wave circuit known as a resonant cavity.

In Figure 11 an attempt is made to picture a progression from the ordinary circuit to a simple self-enclosing resonant-cavity type of circuit. Here we have perhaps the most common impedance in radio engineering, a tuned

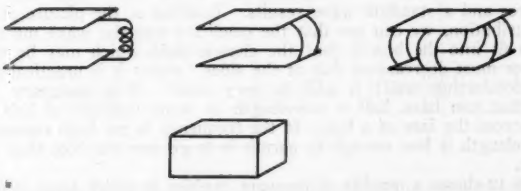


FIGURE 11.—SHOWING STEPS IN PROGRESSING FROM A TUNED PARALLEL CIRCUIT TO A SIMPLE SELF-ENCLOSING RESONANT-CAVITY TYPE OF CIRCUIT.

parallel circuit, the inductance tuning the condenser to resonance and yielding a very high impedance. We still need high impedances in the centimeter-wave frequency band but we do not want radiation. So let us start out with

two plates for our condenser, but first close those plates by a one-turn inductance, this small inductance insuring, if you will, that the resonant circuit will resonate at an extremely high frequency.

Next we put several of these one-turn inductances around the condenser plate; if you wish, you may think of this as many small cross-section inductance bands in parallel, but at any rate, the condenser consisting of the two plates is closed by the surface on which current flows and is closed all the way around.

Now we see that what we have is simply a closed box. Inside lives our centimeter wave. This box may be stimulated in a number of ways and we shall mention some of them later, but at any rate, it still has a resonant frequency; that is, there is a frequency at which there will be very high electric field between condenser plates, at least in the center, due to the charges there, and a very high current up and down the sides of the box. At some time the energy will be in electric field, at a later time it will be in magnetic field.

When you say "circuit" to a centimeter-wave engineer, the picture which comes to his mind is not likely to be close to that which comes to the mind of an engineer working in the radio-broadcast or power range. His concept of circuits is associated with the properties of enclosed regions. Because of the tremendous importance of resonant cavities in the ultrahigh-frequency range, because they form the commonest of our circuits, it is necessary that the engineer have in mind the various resonant modes, the various patterns of electric field and magnetic field and current and charge distribution which can exist in those cavities. So some of his thoughts on electric circuits begin to have similarity to the thoughts of an acoustic engineer about cavities containing sound waves. (This does not imply that centimeter-wave electricity is at all related to sound waves but, because the dimensions of the systems with which we work are of the order of the wave-length, we can expect, and we do indeed find, very similar phenomena in the case of both centimeter-waves and acoustic waves.)

We arrived at this picture of charge and current distribution inside of a box under resonant conditions by extrapolation from the coil and condenser. But we could just as well have obtained it by thinking of the space inside the box as one in which the centimeter-waves are propagating, that is, bouncing back and forth, between walls. We know that when we have a wave going, let us say, from top to bottom and then reflected back toward the top again, there will be a frequency for which the waves will reinforce themselves and a standing wave results. Looking at the picture of electric-field distribution, we can see that the condition that the wave must meet in order to fit into the box is that the electric field which may be high near the center must decrease so that at the sides (where it is practically shorted by the conducting wall) it will be very small. It is necessary, in other words, that you have half a wavelength or some multiple of half a wavelength across the face of a box. If the frequency is not high enough so that the wavelength is low enough to permit it to go into the box, then it cannot resonate.

Figure 12 shows a number of resonant cavities in which some other modes are stimulated. The top three figures are side views of rectangular or cylindrical boxes. The bottom views are of cylindrical boxes. The dotted lines represent electric-field flux lines connecting the positive and negative charges, pictured at one instant's time. These modes in which electric field may distribute itself in resonators are as important to the centimeter-wave engineer as Y and $\wedge$ connections are in the power field and tuned transformers in the radio-receiver field. Notice how you can obtain modes in which there are several nodes and loops of charge distribution or voltage

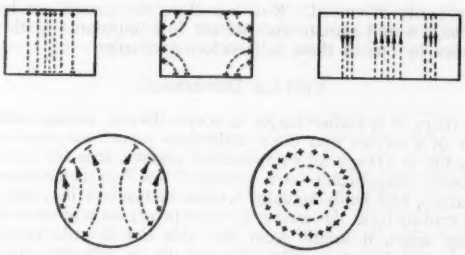


FIGURE 12.—A GROUP OF RESONANT CAVITIES SHOWING THE MODES IN WHICH ELECTRIC FIELDS DISTRIBUTE THEMSELVES.

distribution as you go out from the center. Notice also that there is a mode in which it is not the top and bottom which resonate against each other, as analogous to condenser plates in a parallel tuned circuit, but rather the curved sides of the cylinder.

CIRCUIT FUNCTIONS.

If the centimeter-wave engineer's notion of circuits consists in a large measure of pictures of oscillation modes inside of a closed region, do the operations of these circuits in practical systems involve material conceptual differences as compared to the notions of the use of circuits at the lower frequencies?

Basically, it is probably safe to say that in the utilization of these circuits, the functions of these cavities are in every case analogous to the low-frequency cases. For example, Figure 13 shows a simple filter. Energy comes in by the opening shown with a loop to excite the magnetic field and, if the energy arrives at a frequency that resonates with the box, then very high currents and charges will appear on the wall's faces. Or if you prefer, very high amplitude centimeter-waves will propagate from top to bottom

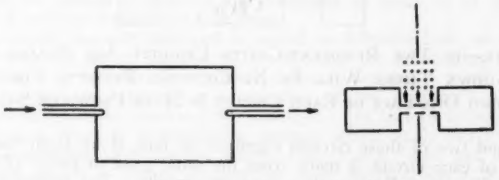


FIGURE 13.—A SIMPLE ULTRAHIGH-FREQUENCY FILTER.

and across the box, thus stimulating a loop on the other side to pick up a good deal of energy and carry it out. But, if the frequency is not at resonance, then this will not happen. Looking at the figure at the right in Figure 13, we set two elements of a vacuum tube, two grids through which an electron beam will pass, the current in that beam containing variations in density so that as each lump of space charge passes by, it induces current in the circuit which connects the two grids according to the principles which

we have previously discussed. Now we close the circuit not by a loop or by a coil, which would radiate and present low impedance at these frequencies, but rather by one of these self-enclosing circuits.

Voltage Difference.

And now there is a rather major concept, that of voltage differences between points of a circuit that often undergoes some "surgery." The notion that a conductor is always an equipotential surface, true for electrostatics, is of course totally inapplicable as a general "law" at frequencies for which currents, charges, and fields actually reverse themselves in a space difference measured in centimeters. However, for two points on a piece of metal a very short distance apart, it might seem that this law is still valid. But even this is not always the case. The common use of self-enclosing conducting systems, such as resonant cavities, very often brings about circumstances in which this persistent but erroneous concept is difficult to reject when one's "voltage difference" ideas have become inbred at lower frequencies.

Since centimeter-waves will fail to penetrate metal to any appreciable degree, it often happens that very high currents flow on one side of a thin piece of metal (Thin compared to wavelength but thick compared to the depth of penetration of the current) with resulting high fields and charges in the metal's vicinity on that side, while on the other side, the region is field-free and the surface is free from charges and currents. For example, the box in Figure 11, if stimulated by a generator on the inside which charges the top and bottom of the box against each other with accompanying high electric field vertically down the center of the box, may be said with care to possess a "voltage difference" between top and bottom (where the "voltage difference" is defined as the integral of the field strength). But an observer, even a very conscientious one, seeking to measure that "voltage difference" between top and bottom from outside the box, will obtain no appreciable reading if the metal of the box has any appreciable thickness. The inside and outside of the metal in this particular case cannot be properly regarded as at the "same potential" even though the thickness of the metal is very small compared to wavelength.

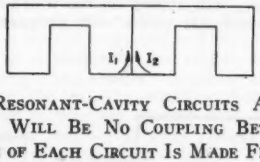


Figure 14.—If Two Resonant-Cavity Circuits Are Placed Together as Shown There Will Be No Coupling Between Circuits Even Though One Face of Each Circuit Is Made From the Same Metal.

If we put two of these circuits together—in fact, if we form them so that one face of each circuit is made from the same piece of metal (Figure 14), we will still not realize coupling between circuits. The return current between the condenser plates of this one resonator will not be coupled to the second circuit to any appreciable degree if the thickness of the metal is made a small fraction of an inch. This means that we must become completely accustomed to thinking of "skin effect" not as a minor effect that makes current move out to the surface but rather as a broad phenomenon that prevents any manifestation of centimeter-waves, be it electric or magnetic field or charge or current, from passing through the surface of a good conductor. Centimeter-wave engineers, though accustomed to making good use in its place of the conventional notions of voltage difference, are becom-

ing equally accustomed to regarding the practical inability of centimeter-waves to penetrate metal a more fundamental concept as a guide to proper use of the less fundamental conventional "voltage difference" concept.

Transmission Lines.

If we could somehow compute how great a percentage of time the average electrical engineer spends on transmission lines and how much on ordinary lumped circuits, the percentage would probably be very much in favor of the latter, even for the radio frequencies. In the microwave region, because the distance between two components of a piece of apparatus is very likely to be many wavelengths if it is any distance at all, the transmission line or wave-guiding system becomes as common as the circuit, and any consideration of physical pictures which the microwave engineer has of basic characteristics of electricity must concern itself equally as much with transmission systems and concepts as with ordinary circuit principles.

As in the case of circuits, we have a problem of preventing radiation. We want to guide the energy, taking it from the source to the place where it will be used, and it is assumed that in this case there is little reason for having it lost on the way. Thus radiation prevention plays a controlling part in the choice of a transmission system in the microwave region. The commonest transmission line is one in which the outer conductor completely encloses the inner conductor as shown in Figure 15. Here, as in the cases

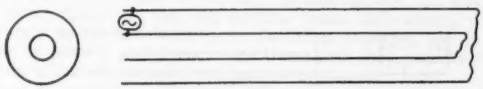


Figure 15.—A Common Type of Transmission Line in Which the Outer Conductor Completely Encloses the Inner Conductor.

we have discussed before, if the centimeter-wave energy is started at one end, it will travel down the line except for the I^2R losses in the conductors and appear at the other end. If the end conditions are not such as to claim all the energy, some may be reflected—go back to the source. But none will leak out of the system if there is any thickness to speak of at all to the metal and if system is closed at both ends.

But the coaxial line acts like, and is indeed no different from, an ordinary cable used even for power frequency. Except that the minimizing of radiation is always present in the centimeter-wave engineer's mind, there is hardly an excuse for claiming a broadening of the engineer's picture of electrical transmission by studying this example. Let us look at some of the more interesting types of wave-guiding systems which apply particularly to the lower centimeter-wave regions which, like coaxial lines, are also self-enclosing and which do indeed require for their appreciation a broadening of concepts of transmission on the part of an engineer who has previously not thought about them. To start with, let us do as we did with the circuit when we considered the condenser plates closed by a one-turn inductance. Take the case of the transmission line in Figure 16 formed of two flat conductors, one type of ordinary open two-wire line. Because of the high ratio of cross-sectional dimensions compared to the wavelength which we can easily attain in the centimeter-wave region, you almost feel intuitively that there should be some mode of distribution of the charge and current so that the charge density will be high at the center between conductors, then fall off so that at the edges the electric field between conductors will be small;

then you can actually close them, forming one rectangular cylinder instead of two lines, and the energy should still progress down the line.

Such indeed is the case, and in Figure 17 is shown a number of cross-sectional arrangements, both cylindrical and rectangular, showing different modes in which the electromagnetic fields may distribute themselves if the cross-sectional dimensions are large enough compared to wavelength.

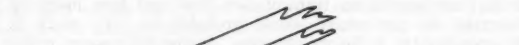


FIGURE 16.—AT THE LEFT IS A TRANSMISSION LINE FORMED OF TWO FLAT CONDUCTORS. IF THE MODE OF DISTRIBUTION IS OF THE TYPE SHOWN AT THE RIGHT, THEN THESE CONDUCTORS CAN BE CLOSED AT THE SIDES.

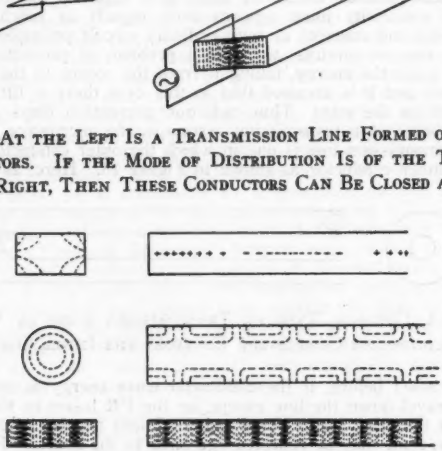


FIGURE 17.—SHOWING MODES IN WHICH ELECTROMAGNETIC FIELDS MAY DISTRIBUTE THEMSELVES IF THE CROSS-SECTIONAL DIMENSIONS OF THE LINES ARE LARGE ENOUGH COMPARED TO WAVELENGTH.

It is not the purpose of this article to discuss the practical advantages of one means of transmission over others, but it is well in passing to note that under certain circumstances the hollow-cylinder, wave-guide type of transmission means results in lower attentuation than can be obtained with the ordinary coaxial line and the need for insulators to hold up the inner conductor is removed. It is rather our purpose here to discuss broadened concepts so that it is important to observe that this new means of transmission, which applies particularly to the centimeter-wave region is one in which the transmission line is highly frequency-responsive, at least near its so-called "cut-off" point. The frequency must be high enough, the wavelength short enough, so that the waves will fit into the cross-sectional dimensions of the hollow cylinder. When this condition is not obeyed (as in the case of longer wavelength oscillations on guides of practical cross-sectional dimensions), the two transmission lines of Figure 16 will be shorted by the sides and, in general, the waves will not "propagate" down the line; whereas above that

frequency they will "propagate" with only the usual I^2R attenuation. The importance of the waveguide has brought the matter of wavelength versus cross-sectional dimensions into the centimeter-wave engineer's pictures of transmission in just as important a role as important concepts like, say, "characteristic impedance."

Radiation.

We have discussed now how the word "circuit" has expanded in its meaning to cover the centimeter-wave band and how the notions of transmission lines have broadened somewhat to include new effects. There remains the third general division of the control and guiding of electromagnetic energy, radiation; radiation, that is, as a desirable, intended effect, not simply as an objectionable by-product in circuits and transmission lines.

There are two rather obvious and quite well-known expansions in our notions of radiators that come about because of the work of the last several years in the centimeter-wave region. One is, of course, that because the wavelengths are shorter, it becomes practical to use reflectors, borrowing them from the light part of the spectrum, where such devices have long been used to concentrate wave energy in beams. Also, the acoustic analyses carry over and we find it possible to use such radiators as horns.

There are some other things, however, that are happening to our notions of radiation of electromagnetic energy, primarily due to efforts in the centimeter-wave range in the last several years and which, though they belong properly under the heading of radiation concepts, tie in so closely with notions of circuits and transmission lines that they make a fitting summary for the whole discussion that has been presented here.

The reader is probably willing to accept now the point of view, which centimeter-wave engineers have come to know and accept, that the radiation of electromagnetic energy is not an entirely distinct phenomenon from the guiding of such energy around a circuit or along a transmission line. All three classes are properly being thought of as guides of a sort, manifestations of the same phenomena, differing only in the relative magnitudes of their common characteristics. If the conducting and dielectric boundaries are so situated around the source that the energy is mainly contained and dissipated in a relatively small region, then the system is usually thought of as a circuit. If the boundary shapes are such that the energy is guided along a somewhat longer path and absorbed or reflected at the termination, with the losses to the surroundings again relatively small, then it is probably best termed a transmission system, line or guide. If the boundaries are such as to draw the energy out of the source and encourage it to continue on through free space with little or no further guidance and with relatively little reflected back to source, it is an efficient radiator (antenna).

These pictures are, of course, equally applicable to the lower frequencies, but radiation is so much less a factor in circuits and lines that it is natural for us to become accustomed to using only Kirchoff's laws and ohmic dissipation, whether for lumped circuits or distributed constant networks like transmission lines. The possibility of loss of energy by radiation is thus often disregarded in circuits and lines and regarded as an entirely separate phenomenon when it occurs in antennas. Not only the proportionately greater amount of loss of energy by radiation at ultrahigh frequencies in ordinary circuits and lines, but also the greater need of appreciation of the wave nature of electricity, whether standing or travelling waves, on systems of small physical dimensions has emphasized the more basic picture and is serving to correlate the three main divisions in the controlling or guiding of electromagnetic energy: circuits, transmission lines, and antennas.

"HELIARC" WELDING.

This new method of fusion welding, which takes advantage of the peculiar properties of helium, an inert, nonexplosive, nonflammable gas, is the result of joint development by the Dow Chemical Company and Northrop Aircraft, Incorporated. T. E. Piper, Process Engineer of Northrop Aircraft, presented this paper at a June meeting of the Los Angeles Section of the American Welding Society. His paper is reprinted from the November, 1942, Welding Journal. A paper on the metallurgical aspects of Heliarc welding was presented at the annual meeting of the American Welding Society in October by Dow Chemical Company representatives. That paper has been published in the December, 1942, issue of the Welding Journal.

Culminating research over a two-year period, Northrop Aircraft, Inc., is introducing and giving to the war industries "Heliarc" welding, and trusts that this new method of arc welding will prove a tangible weapon promulgating to some extent the defeat of our enemy. This new method of arc welding has made possible the use of a new material for aircraft construction which lies in inexhaustible quantities off our own shores, and it has simplified methods of construction that will speed plane output. This innovation has been made possible by the courage and perseverance of two men, Mr. V. H. Pavlecka, Chief of Research, and Russ Meredith, Welding Engineer, together with other men of the Northrop organization who believed in them. This new development permits the arc welding of magnesium sheets, extrusions and tubing into structures simpler, lighter and stiffer than is possible in conventional duralumin construction. At the same time, methods of treating magnesium to make it less inflammable and more resistant to heat have been perfected.

The use of magnesium welded structures eliminates the hundreds of thousands of rivets that go into the conventional plane. Rivet heads on the fuselage and wings, even though countersunk, produce resistance to passage through the air, or "parasite drag." At high speeds a substantial portion of the engine power is used to overcome this parasite resistance. In the future, welded magnesium aircraft can be finished just as smoothly as a fine automobile, presenting to the airflow a perfectly uniform and rigid surface.

While magnesium has been used for some time in the aircraft industry for engine parts, wheels and accessories it has never before been used extensively as a primary construction material because of the difficulties in fabricating. The Northrop "Heliarc" welding process makes possible the all-magnesium plane with its many advantages.

Magnesium is the most abundant metal on the earth and in the ocean. Indeed, about 15 per cent of all the dissolved solid matter in the sea consists of magnesium chloride and magnesium sulphate—enough to cover all the land areas of the earth to a depth of 60 or 70 feet or 9,000,000,000 pounds per cubic mile. The mother liquors from the brine of salt wells are always rich both in magnesium salts and bromides. Nearly all the silicate rocks of the earth's crust contain notable quantities of magnesium. Some of these are of commercial importance; examples are talc, soapstone and asbestos, cement and marble. The cost of magnesium alloys at the present time is greater than aluminum alloys. However, because of new magnesium plants under construction and increased production in the plants now in operation, magnesium alloys will be cheaper than aluminum alloys in a very short time. 24,000 Kw.-hr. are required to produce a ton of aluminum from Bauxite and only 18,300 Kw.-hr. are required to produce a ton of magnesium, which has 54 per cent more volume. Magnesium alloy will shortly be the most

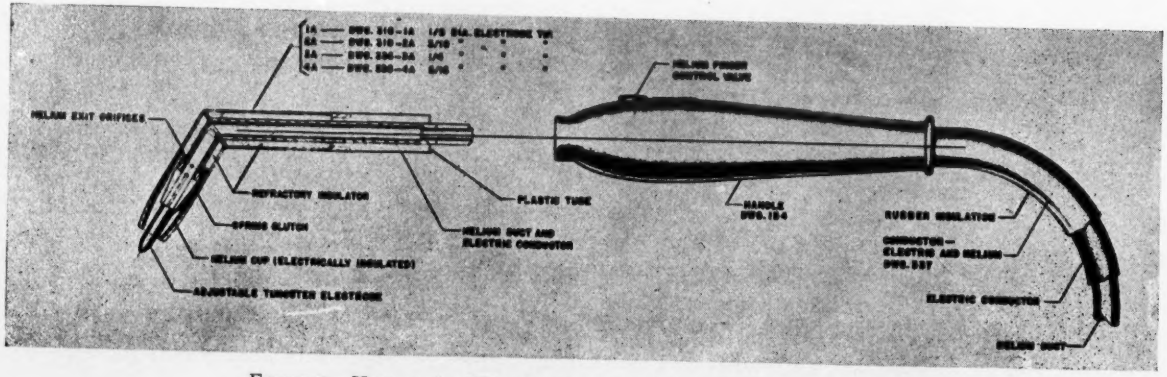


FIGURE 1.—HELIUM ARC-WELDING TORCH AS USED FOR MAGNESIUM ALLOYS.

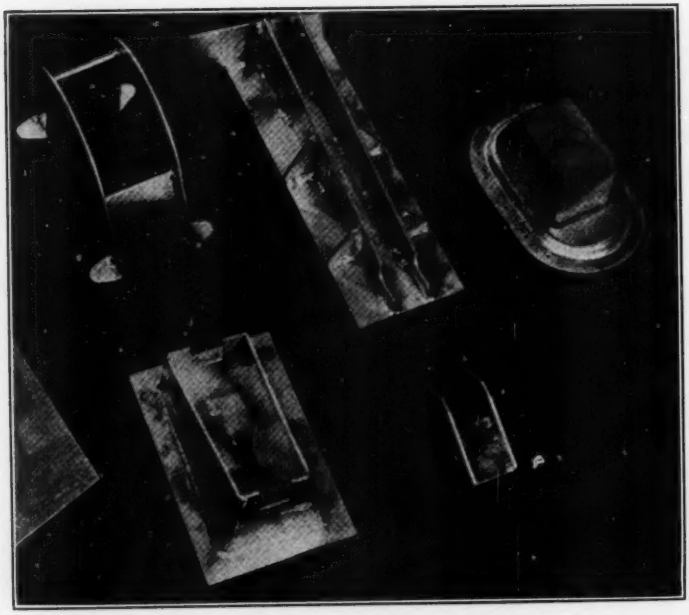


FIGURE 2.—PHOTOGRAPH OF SPECIMENS OF WELDING.

FIGURE 3.—PHOTOGRAPH OF HELIARC WELDER AT WORK.

FIGURE 4.—MICROPHOTOGRAPH OF GRAIN STRUCTURE OF WELD. × 500.

Acetic acid etch showing weld fusion or blending characteristics of weld ingot with parent metal. Weld ingot (darker half of print) made of Dowmetal J alloy rod blended with Dowmetal J parent metal (lighter half of print).

plentiful alloy if it is not at the present time. The world's largest deposits of Brusite, a magnesium bearing ore, are in Montana, Washington and British Columbia.

Contrary to popular belief, magnesium alloys are not inflammable when properly processed; in fact they are more resistant to direct flames than aluminum alloys. Although magnesium alloys are 35 per cent lighter than aluminum alloys and 21 per cent of the weight of steel per unit volume, their weight strength ratio is comparable to aluminum alloys, and they possess the design property of stiffness and rigidity that cannot be obtained in other alloys. With these properties of magnesium alloys in mind, together with the rapid production method of attachment and aerodynamic advantages which Heliarc welding presents, the future use of magnesium alloys for the fabrication of structures, especially in aircraft, should be greatly enhanced.

Magnesium castings containing foundry defects have been repaired with this process and welds equal to or stronger than the surrounding metal have been obtained. The weld metal is much more dense than that of the surrounding cast metal and far less susceptible to corrosion. Almost any thickness of cast metal that can be poured may be readily welded with this process.

Welding rod of the same alloy as the parent metal is usually used for castings and wrought alloys. The weld ingot appears to have better corrosion-resistant properties than the parent metal in salt spray tests. The weld bead appears to be cathodic to the adjoining metal, which causes minor pitting of the original metal adjacent to the weld under severely corrosive conditions.

The tungsten electrode is very slowly alloyed with the weld metal and naturally in a period of time the tungsten electrode must be replaced. No noticeable increase in the corrosion rate of Heliarc welds in magnesium alloys because of the presence of tungsten has been noticed.

Heliarc weld ingots have in general an extremely fine grain with practically no grain enlargement adjacent to the bead, indicating that there is a minimum of heating effects on the adjacent metal. This accounts for the very good weld efficiencies obtained on Heliarc welded alloys.

Dowmetal J-IH magnesium alloy, Heliarc welded, has approximately 95 per cent of the parent metal strength in the weld area. However, at present the design safety factor for welded dowmetal J-IH assemblies is 75 per cent of the strength of the parent metal. These strength values are based on butt-welded joints. Fillet, lap, edge or corner welds are weaker than the butt-welded joint and must be stressed accordingly.

Heliarc welding has proved to be a successful medium of attachment for magnesium, stainless steel, brass, inconel, monel and some of the carbon steel alloys. Research work is now in progress to extend its use to aluminum and other carbon steel alloys not heretofore Heliarc welded. In the Heliarc welding process, a shield of helium gas envelops the molten metal. Because helium gas is an inert gas, it prevents oxidation and eliminates the use of a flux and the danger of entrapped flux in the weld ingot that would promote corrosion. The arc in this process is produced directly between a tungsten electrode and the base metal rather than between two tungsten electrodes as is the practice in atomic hydrogen welding.

The Northrop Heliarc welding torch is equipped with a helium valve that is opened just prior to the striking of the arc between the tungsten and the parent metal which feeds helium through the torch to the weld. Helium has over five times the specific heat of air and when in motion prevents heat accumulation around the weld thereby keeping it cooler and giving a better fusion and penetration with less distortion than other welding processes. The arc is struck by a light brushing action and quickly drawn

back from the metal. Northrop Aircraft, Inc., has designed Heliarc torches which will shortly be available to the industry. The torches are of two sizes to handle 1/16 to 1/8-inch electrode and 3/16 to 1/4-inch electrode, respectively, and may be supplied with tips of different angles 40 degrees, 60 degrees and 90 degrees. The torch may be used for pencil welding or, by extending the handle a handle bar grip is obtained for heavier welding. A type of torch will later be available that feeds the filler rod automatically, giving more uniform results than where the rod is fed by hand. Best results are obtained by feeding the filler rod into the tungsten electrode which melts off portions of the rod thereby casting a uniform weld ingot. This procedure has been found to be superior to the practice of feeding the filler rod into the molten pool under the arc, whereby the molten pool is not sufficiently agitated to break the crust which gathers on the surface of the pool. Since the reflected heat from the tungsten overheats the filler rod, an angle of 60 to 90 degrees must be maintained between the filler rod and the electrode. The tungsten electrode varies in size from 1/16 to 1/4-inch, depending upon the thickness of metal welded and the heat required. The torch must be held as near the weld as possible to obtain maximum benefit from helium for the prevention of oxidation. Also an arc length of 0.060 inch maximum should be maintained. Poor penetration or gas holes may result by using too long an arc. On those alloys that have a tendency to be hot short, a rapid welding speed is recommended, approximately three feet per minute, to eliminate the danger of cracking.

A conventional arc welding machine with direct current generator having a 150-ampere output is desirable. However, higher output machines which operate at less than 300 amperes may be used providing lower amperes may be obtained. An upright machine is preferable in that it is easier to attach a helium tank to such a unit. Separate amperage and voltage regulators must be provided and the machines should have a continuous sequence of five increments of current control. The average life of a 200 cubic foot helium tank is about 35 hours of continuous welding with a medium-sized torch. Fairly pure helium gas is required. Normally helium as purchased from the Government plant is sufficiently pure to cause no difficulty. Additional gases in helium such as carbon dioxide, hydrogen, nitrogen and the hydro-carbons may cause pronounced defects. Hydrogen produces bad porosity. Oxygen films the metal causing poor coalescence and inclusions. The presence of 7 per cent nitrogen in the helium reduces the welding speed to about two-thirds that obtained when only 2 per cent is present. All of these gases if present, may be removed, however, by passing the helium through filtering mediums.

This method of arc welding has provided an important new tool for the fabrication of structures from alloys such as magnesium and stainless steel. Any type of joint which has been commonly used for welding ferrous metals, may be employed on magnesium and stainless steel.

Stainless steel has heretofore been the most difficult alloy to weld and could only be satisfactorily arc welded by the use of atomic hydrogen, and then only on thicker sections. By the Heliarc welding process, thicknesses of less than 0.010 inch may be very easily welded. In the Heliarc welding of stabilized stainless steel the extent of carbide precipitation is very low as compared to other methods of welding, which greatly increases its fatigue factor. The medical profession would do well to consider this process for the arc welding of stainless steel braces in bone surgery where spotwelding and other means of attachment have not been so successful.

In the Heliarc welding of magnesium structures a tungsten electrode is used with reversed polarity making the magnesium the anode. For ferrous and copper alloys, a carbon electrode is used and the welded structure is the cathode. Craters are eliminated in reverse polarity welding.

For the high temperature melting and heat resisting alloys Heliarc welding has proved successful where other welding methods failed. Heliarc welding gives the greatest penetration of any known welding process.

MARINE GEARS AND THEIR MAINTENANCE.

This article is reprinted from the Nautical Gazette, September, 1942. The author, C. R. Waller, is Vice-President and Chief Engineer of the De Laval Steam Turbine Company.

Most of the new steam-driven ships are equipped with geared turbines and the gear reductions used may, or may not, have been built in the same shop where the turbines were manufactured. They should, therefore, be considered as a complete unit in themselves, forming part of the propelling equipment.

The chief engineer on a ship, and his assistants, must have adequate knowledge of many items in connection with the reduction gear in order to operate it satisfactorily and to take care of the equipment. With this thought in mind, the present article has been prepared for their assistance. It must be recognized that the high-speed, high-power reduction gear is one of the most important parts of the propelling equipment and that its satisfactory operation will, to a great measure, depend on the watchfulness of the operator. Present day experience with marine gears has been quite satisfactory as compared with the difficulties that were encountered during World War I. This can be attributed only to the increased skill of the manufacturers and the longer experience of the operating engineer.

Rather than to go into the details of gear design, our purpose is to point out the importance of the operator and of his knowledge of this type of machinery in safeguarding against unnecessary shutdowns. We start with the assumption that the gear reduction has left its place of manufacture and has been accepted as a finished and complete piece of machinery, free from inherent defects, and has arrived at the shipyard to be installed in a merchant ship.

The shipyard's responsibility is great, as in handling the equipment upon its arrival and after it reaches the shipyard in a fully assembled condition or in disassembled sections, extraordinary care must be used to safeguard the gears, especially during installation. The shipyard will generally gain time and save expense by consulting the manufacturer's erecting engineer, who is in a better position to advise how to handle such equipment. Except for comparatively small gear reductions, it is necessary to ship the unit disassembled, as in most cases the main reduction gear is of such proportions and size that it could not be properly transported if assembled in its gear case. Before shipment from the manufacturer all parts, stationary and revolving, are well protected against the elements by the use of non-rusting sludge, waterproof paper, etc., and under no considerations should the protecting coating be removed or tampered with until the parts are ready to be assembled in the ship.

The shipbuilder is, of course, responsible for the design of the structure in the ship, including the foundation on which the gear reduction is placed. The foundation design is vitally important to the satisfactory operation of the gear and close cooperation between gear manufacturers and shipbuilders is essential. The distribution of the load over the foundation must be studied so that the longitudinal and transverse girder construction of the foundation will coincide with the structural design of the gear case itself.

In any case, the foundation must be stable and at no time, under any adverse sea or operating condition, should the movement of the ship's structure affect the permanency of the foundation structure to which the gear case is bolted.

The installation of the gear reduction in a ship must be carried out with the utmost care and the gear manufacturer should furnish such data and information from the shop records as are necessary to permit of the gear case being installed in a manner duplicating the alignment of all component parts as they existed when assembled in the machine shop. The placing of chocks and metal contacts between gear case flanges and foundation surfaces, and the provision of an adequate number of fitted bolts, are all details that must be carried out with greatest care.

The final inspection after completion of installation, must include verification that contacts between pinion teeth and gear teeth are maintained with the same degree of perfection as when the gears were passed by the manufacturer's inspector. A set of bridge gage readings taken in the manufacturer's shop or on board ship should be part of the ship's record for future reference.

Assuming that we have a well designed gear reduction, adequate foundations and correct installation, what methods should the operating engineer taking over set up to guard against mistreatment of the gears during operation? His first check is to be sure that the first and initial starting is well planned and correctly carried out. Invariably the shipyard is responsible for the initial starting, which ordinarily takes place prior to dock trial and spinning tests, and one of the most important details at that time is to see that the oiling system is clean. During the erection work in the engine room, constant vigilance is necessary to safeguard all interior parts of the gear reduction, all piping and auxiliary equipment from foreign matter of any nature. It is found advisable to blank off the oil feed line serving the main unit bearings and sprays and to install a three-inch by-pass temporarily, so that no flushing oil comes in contact with bearings and gears. While this permits of completely flushing all external piping, tanks, coolers, etc., it prevents scale and other foreign matter from getting into the internal parts of the main unit. As all bearings and internal parts are clean when the unit is closed after installation, it is desirable to protect these parts from dirty oil. After the external system has been flushed and cleaned, it is recommended that the regular lubricating oil be heated to 140 degrees-160 degrees F. and circulated at this temperature through the complete system for at least twelve hours, the main unit being at the same time turned by the turning gear.

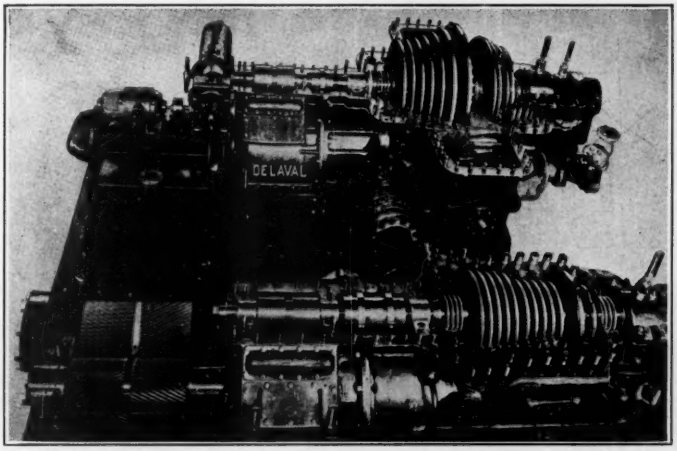
Since the oiling system is the most important auxiliary of a gear reduction, a brief general resume of its component parts will be given. Any lubricating system for a gear reduction has fundamentally two functions: first, to lubricate all moving parts adequately, and, second, to remove the heat imparted to the oil by running friction and the heat conducted through shafts that may be subjected to high operating temperatures (turbine shafts).

An oiling system suitable for performing these functions and for operating continuously must comprise the following:

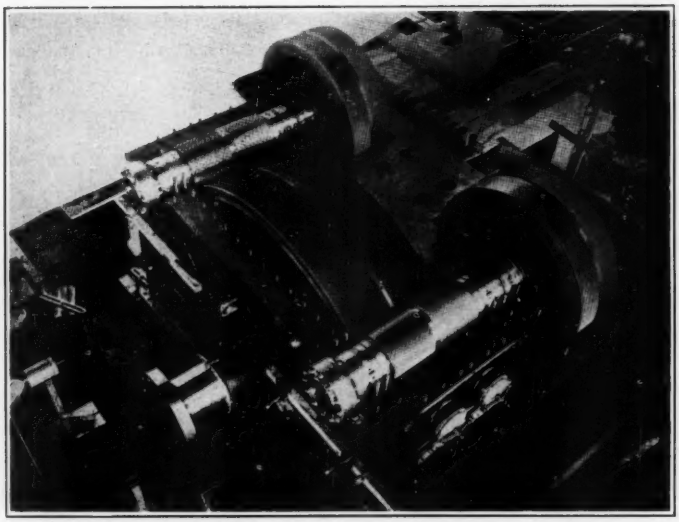
1—Sump tank (preferably of a size to hold all the oil in the system, but not less than the capacity of the overhead service tank).

2—Circulating pumps. (The two pumps should be of the same capacity. The circulating rate of these pumps should be at least 20 per cent greater than the circulating rate specified by the manufacturer. It is recommended that one of these pumps be steam-driven).

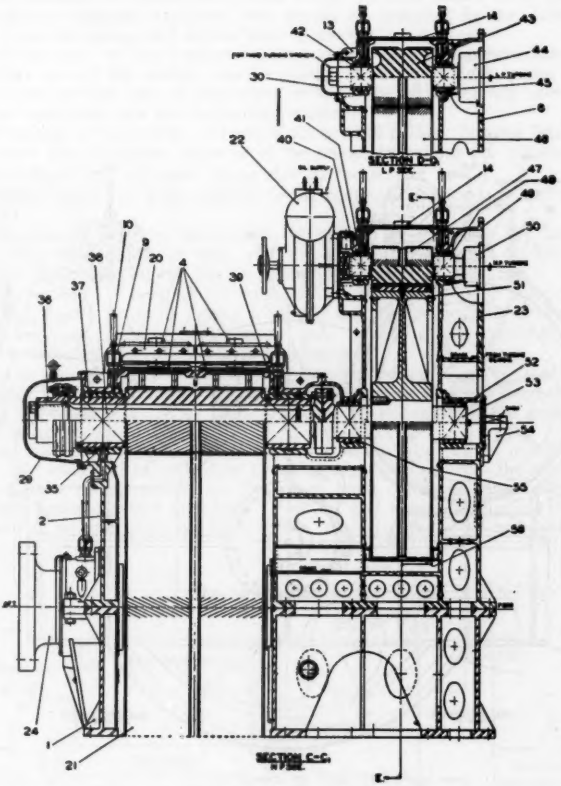
De Laval Gears in a 34,000 SHP, Twin Screw Passenger Ship.



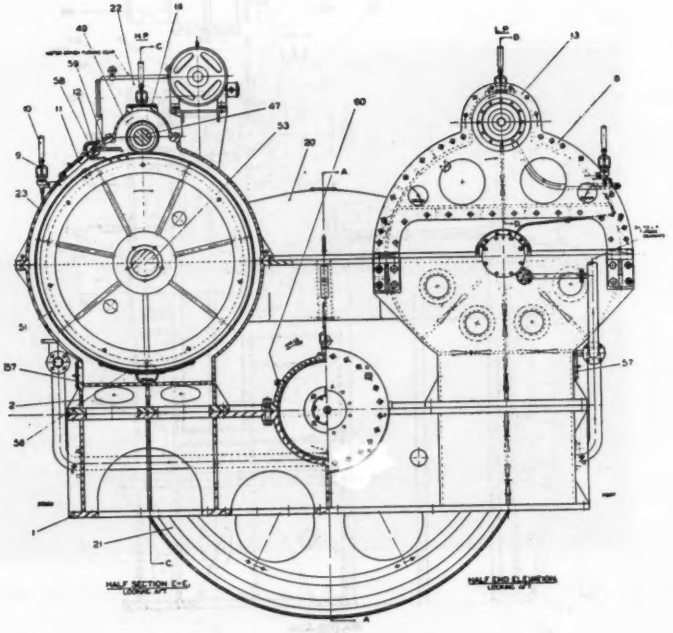
Compound Turbines and Double Reduction Gears Assembled in Shop With Turbine Casting Covers and Pinion Covers Removed.



Gear of This Type Transmits 6750 SHP. at 95 RPM. With a Maximum of 7600 SHP. at 99 RPM.



1 Lower Case
2 Intermediate Case
4 Inspection Plate
8 Upper Case, L.P.
9 Oil Flow Indicator
10 Thermometer
12 Upper Case Cover, L.P.
14 Inspection Plate
20 Intermediate Case Cover
21 Low Speed Gear
22 Turning Gear
23 Upper Case, H.P.
24 Low Speed Gear Shaft
29 Coupling Guard
30 Cover
35 Bearing
36 Intermediate Speed Coupling
37 Intermediate Speed Pinion, H.P.
38 Quill Shaft, H.P.
39 Bearing
40 Inspection Plug
41 Bearing
42 Bearing
43 High Speed Pinion, L.P.
44 High Speed Coupling
45 Bearing
46 Intermediate Speed Gear, L.P.
47 High Speed Pinion, H.P.
48 Bearing
49 Upper Case Cover, H.P.
50 High Speed Coupling
51 Intermediate Speed Gear, H.P.
52 Bearing
53 Intermediate Speed Gear Shaft, H.P.
54 Turbine Bracket
55 Bearing
56 Baffle



1	Lower Case	22	Turning Gear
2	Intermediate Case	23	Upper Case, H.P.
8	Upper Case, L.P.	47	High Speed Pinion, H.P.
9	Oil Flow Indicator	48	Upper Case Cover, H.P.
10	Thermometer	51	Intermediate Speed Gear, H.P.
11	Inspection Plate	53	Intermediate Speed Gear Shaft, h.P.
12	Spray Nozzle Cover	54	Baffle
13	Upper Case Cover, L.P.	57	Inspection Plate
14	Inspection Plate	58	Oil Strainer
20	Intermediate Case Cover	59	Gear Spray Nozzle
21	Low Speed Gear	60	Inspection Plug

3—Oil strainer. (The strainer must be of the twin-basket type, permitting cleaning without shutdown, and should be installed in the discharge piping from the pump and within easy access).

4—Oil coolers. (Two duplicate coolers should be used, so interconnected that either one of the coolers can be placed in service. Each cooler must be of a size to take care of heat removal from the oil under any operating condition and with any sea water temperature).

5—Overhead service tank. (To hold about 1000 gallons, but not less than three times the circulating capacity of the pumps in gallons per minute).

6—Overhead dirty-oil tank (same size as the service tank).

7—Storage tank (to hold capacity of the combined service tank and dirty-oil tank).

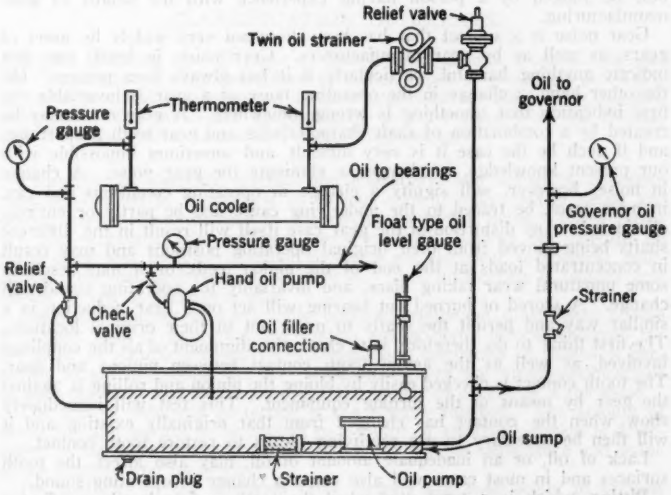
8—Illuminated overflow observation fitting (to be placed in the line between the overhead service tank and the inlet oil connection on the gear reduction, preferably on the engine room floor level).

9—Oil purifier (to handle approximately 200 gallons per hour and so connected that it can draw its supply from any one of the overhead tanks).

Should a direct pressure system be used instead of an overhead tank, gravity system, the service tank can be eliminated.

The lubricating oil recommended for marine reduction gears is a good, high-grade, pure mineral oil, having a viscosity of 300 to 350 Saybolt seconds at 100 degrees F. The temperature of the oil entering the gear case should be about 100 to 110 degrees F.

While the gear reduction is not supposed to be adjusted or manipulated during operation and in itself does not need any attention from the operating personnel, the oiling system, on the other hand, must be observed at all times and needs constant attention. Poor oil and a neglected oiling system will ruin a marine gear, no matter how perfectly the gear was designed



PRESSURE OILING SYSTEM FOR GEARED TURBINE PROPULSION UNIT.

and installed. It is, therefore, essential that the operating personnel follow a regular and specific routine in the care of the oiling system. The chief engineer must be familiar with the characteristics of the particular oil that he is using and should have adequate means at his disposal to be able to judge the sample of oil that should be taken from the system daily.

The operator should keep constant watch on the oil and use his facilities to remove any water that may have entered the system. The oil separator should be run at least eight hours of the twenty-four. The water pressure used for the oil cooler should be less than the oil pressure, and the glands on the turbine shaft must be adjusted to prevent steam leakage along the shafts. To take care of changing temperatures, the sump tank may be provided with a breather pipe, preferably installed within the engine room.

If, after some time in service, the operating sound of the gear changes and the smoothness of its operation is affected, these are indications that an internal inspection of the reduction gear should be made in the endeavor to locate the cause. Always remember that something doesn't "just happen" with a gear any more than with any other piece of machinery, and if a change occurs, there must be an underlying cause to create such a change. It is up to the operator to be able to diagnose the ailment and to find a suitable remedy. The problem is manifold and sometimes rather involved, and it may take a long time to solve by means of carefully followed up inspections. It is, therefore, of the greatest importance that the operator keep a definite record of gear operation and inspection from the very beginning, in order to be prepared to discuss the situation intelligently with the gear manufacturers expert. Outside of the care of the oiling system and the possibility of a bearing wiping or burning, the operator should never attempt to make any corrections or adjustments without the advice of a competent representative of the gear manufacturer. Pinions and gears are made in a special hobbing machine and any change in the tooth surfaces can best be judged by a person having experience with the details of gear manufacturing.

Gear noise is a subject that has been discussed very widely by users of gears, as well as by gear manufacturers. Gear noise, in itself, may not indicate anything harmful, particularly if it has always been present. On the other hand, a change in the operating noise of a gear is invariably the first indication that something is wrong somewhere. A gear noise may be created by a combination of shaft characteristics and gear teeth proportions, and if such be the case it is very difficult, and sometimes impossible with our present knowledge, to change or eliminate the gear noise. A change in noise, however, will signify a change in operating conditions and can, in most cases, be traced to the underlying cause and be partly or entirely eliminated. Any distortion of the gear case itself will result in the different shafts being moved from their original operating positions and may result in concentrated loads at the end of the pinion teeth, or it may result in some unnatural wear taking place, and invariably the operating sound will change. A scored or burned out bearing will act on a gear reduction in a similar way and permit the shafts to move out of their original locations. The first thing to do, therefore, is to check the alignment of all the couplings involved, as well as the actual tooth contact between pinions and gear. The tooth contact is checked easily by bluing the pinion and rolling it against the gear by means of the turning equipment. This test will immediately show when the contact has changed from that originally existing and it will then be necessary to use rectifying means to restore tooth contact.

Lack of oil, or an inadequate amount of oil, may also affect the tooth surfaces and in most cases will also cause a change in operating sound.

Pitting, which is a term used when the tooth surface has been affected sufficiently to actually remove flakes from the surface of the teeth, may be

caused by poor oil or by abnormal load conditions. From experience it has been learned that the second reduction gear is more apt to show pitting than are the first reduction gears. In many cases such pitting ceases after a time and in some degree seems to correct itself. Pitting in many cases has little or no effect on the life of the gear.

If it is at all possible, it is recommended that new gear reductions be operated at reduced power for several thousand miles in order to permit the gears to "run in". This precaution will prolong the life of the gear. The second reduction gear is invariably wider in working face than the first reduction gear and when new will often show heavy contacts for about two inches at the extreme ends of the gear teeth. Such a condition will better rectify itself if the gear be operated at lighter load when new.

When judging the appearance of a tooth surface after the gear has been in operation, it is of the utmost importance to note the location of the affected section and its magnitude. Periodic inspections and the keeping of accurate records are, therefore, essential in order to guard against serious trouble.

If at any time a bearing is ruined and has to be replaced, care must be used to determine whether the affected bearing alone should be changed, or the complete set of bearings for the shaft should be renewed. A slight wearing of bearings will have no ill effect on the operation of the gear, providing all bearings on the same shaft wear uniformly. On the other hand, if any one bearing wears more than the other, it will cause a change in the location of the shaft that must be rectified.

Whenever a gear reduction is completely disassembled for cleaning or general overhaul, a complete check must be made in reassembling to ascertain that the tooth contacts are in line with the original records.

CLASSIFICATION OF RELAYS.

In the following several pages of tables, R. B. Immel, Control Engineer for Westinghouse, classifies relays by fifteen types of protection or control in order to simplify selection of suitable protection for electrically operated equipment. The tables and accompanying text are taken from the October and November, 1942, issues of Product Engineering.

Protection of electrical circuits and machinery, and automatic operation may be obtained by proper use of various control relays which detect and thwart certain abnormalities in the circuit or in the drive. These relays are not necessarily the ordinary electromagnetic devices but operate on many principles, the most common of which are electrical, mechanical, magnetical, chemical, and thermal phenomena. Each application is usually best served by one of these principles.

Since the designer of electrically operated equipment must often choose a suitable type of protection and control among many devices designed for the same or similar service, the accompanying tabulation of relays is presented to aid in making the best selection. There are many modifications of each device in use, but in general the principle of operation is the same.

The cost of complete protection is not always justified. The amount of protection and control to be applied to a motor or electrical system is determined by balancing the cost of protection against the importance and value of the machine and its product.

The majority of the tabulated relay circuits are used solely to prevent overheating, which damages insulation as indicated in Figure 1. Overheating

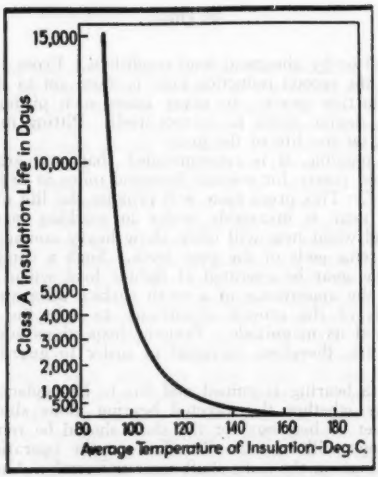
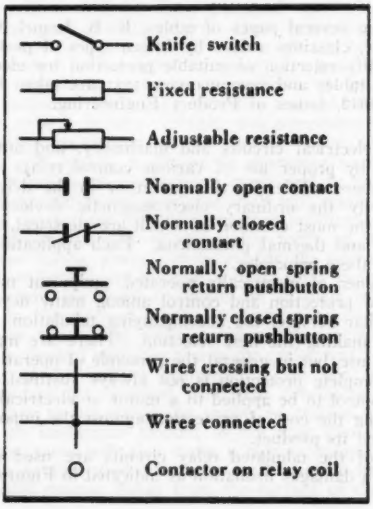
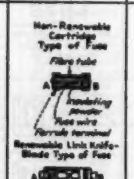
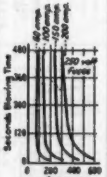
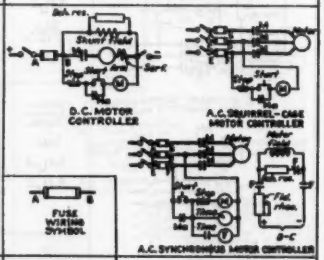
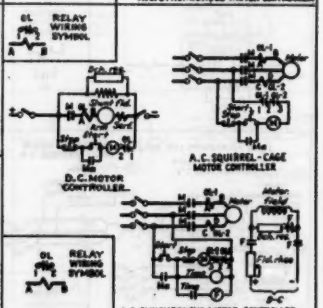
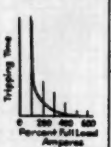


FIGURE 1.—RELATION BETWEEN LIFE AND TEMPERATURE OF CLASS A INSULATION WHEN TESTED IN A CONSTANT TEMPERATURE OVEN. IN ACTUAL SERVICE THE LIFE IS USUALLY MUCH SHORTER BECAUSE OF THE EFFECTS OF DIRT, MOISTURE, MECHANICAL STRESSES, CORROSIVE FUMES, AND OTHER INDETERMINABLE FACTORS.

SYMBOLS USED IN THE ELECTRICAL DIAGRAMS CONTAINED IN THE TABLE ON THE FOLLOWING PAGES.

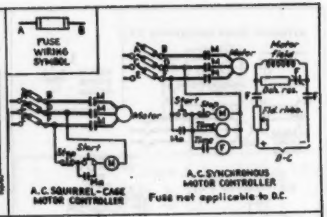


I—OVERLOAD PROTECTION

Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
1 Fuse. A fuse is used when overload and short-circuit protection cost must be minimized. When applying fuses, maximum ratings should approximate 150% full load current of d.c. and a.c. wound rotor motors, and 250% to 300% of full load current of squirrel-cage motors.		Properly applied fuse carries 110% full load current indefinitely. At 150% full load current, fuse link melts and breaks circuit in specified time in accordance with rating.		
2 Instantaneous Magnetic Relay. Protects against high overloads. Usually calibrated to trip instantaneously at a current above motor peak starting current. Interrupting capacity of line contactor determines maximum current that can be interrupted safely.		Current through coil produces force tending to lift armature and to break contacts. Weights or springs opposing armature movement determine current values at which relay instantly trips.		
3 Time Delay Magnetic Relay. Protects running motor against sustained currents only slightly above full load current. Dash-pot or other damping means prevents tripping on peak starting current or momentary high overloads.		Addition of dash-pot to No. 2 relay prevents tripping on starting or momentary high currents. Delay period is inversely proportional to sustained overload current. De-energization of power circuit after relay operation permits instant return of armature. Relay may be designed for closing or resetting contacts automatically, manually or electrically. Number of turns and current capacity of coil determine specific rating.		

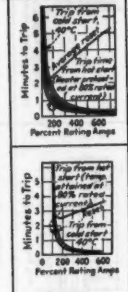
4 De-ion Boric Acid Power Fuse. Used with low interrupting capacity switches on a.c. circuits to obtain high interrupting capacity. Installation of single circuit breaker of equal capacity and disconnecting means usually costs 20% to 50% more. Fuse is usually arranged to serve also as a means of disconnection. Links are renewable in ratings of 7.5, 15, 25, and 34.5 kv with interrupting capacities of 0.45, 0.75, 1.0 and 1.2 million kva respectively.

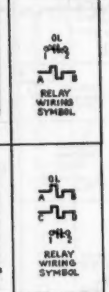
At certain current value main fuse link burns out and releases plunger, which pulls a.c. arc through boric acid in center of tube. Auxiliary fuse wire interrupts small arc. Larger arc is extinguished by de-ionizing action of water vapor, which is produced by reaction between arc and boric acid, when de-ionization of air medium exceeds rate of ionization by the arc.

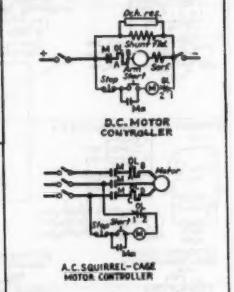


5 Thermal Overload Relay. Protects against sustained overload currents at 115% to 125% full load motor current to values slightly exceeding locked rotor current. Usually ideal for running protection because thermal lag prevents tripping on starting or momentary high currents. Two separate relays or a combination relay with two or more current elements are usually employed on 3-phase a.c. circuits to protect all phases and prevent the motor operating on single phase. Relay must have fuse or circuit-breaker protection against short circuits.

Heat expands one side of bimetallic disk or strip more than the other, thus causing warping or deflection which will make or break a contact. Since deflection of flat strip is slow, a quick acting contact mechanism is usually employed to prevent burning of contacts. Disk type elements reverse convexity suddenly. Tripping time is inversely proportional to sustained overload current. Cooling rate of bimetal determines times for reset. Relays may have automatic or manual reset.

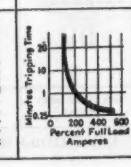

Minutes to Trip
Trip from cold start, 40°C ambient
Trip time from hot start (Temp. attained at 100% rated current)
Percent Rating Amps
Minutes to Trip
Trip from hot start (Temp. attained at 100% rated current)
Trip from cold start 40°C
Percent Rating Amps

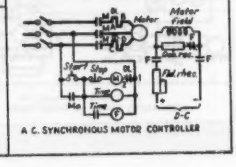




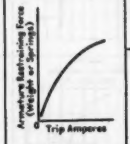
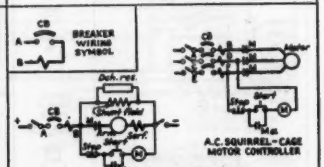
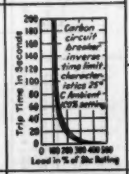
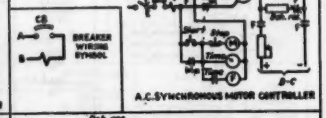
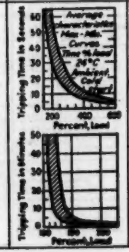
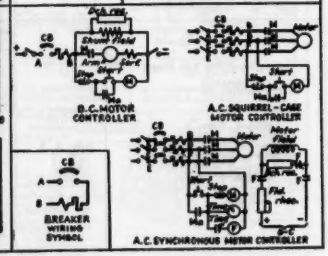
6 Thermal Melting Alloy Relay. Gives inverse time limit protection against sustained overload. Usually designed for manual reset since there is no automatic force available for resetting.

Ratchet wheel and shaft, to which torque is applied through spring latch, are restrained from rotating by low melting alloy in bearing box. Melting of alloy at predetermined temperature produced by heating coil when sustained overload current occurs, permits contacts to open. Resetting awaits refreezing of alloy. All friction is overcome by use of a strong operating spring.

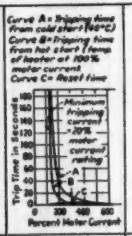
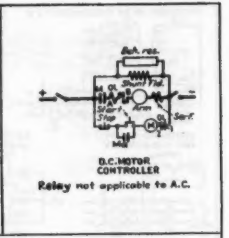
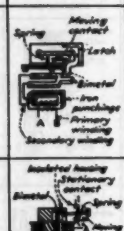
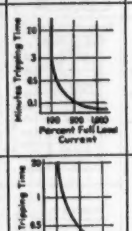
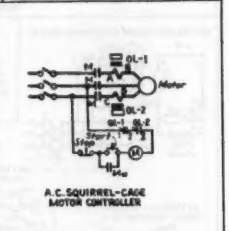
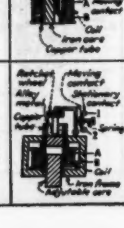
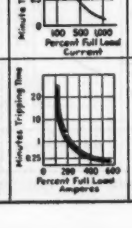
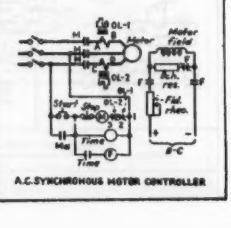
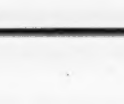
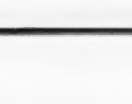
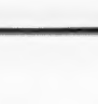




I—OVERLOAD PROTECTION (*continued*)

Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
7 Instantaneous Magnetic Trip Circuit-Breaker. Air circuit-breakers have higher interrupting current capacity than most contactors. They may be considered a combination of overload relay and circuit opening device. They are often made for a multiplicity of main circuits and may be equipped with various operating and tripping mechanisms.		Magnetically actuated tripping pin opens toggle held arcing contact and main current carrying contacts at specified overload current.		
8 Time Delay Magnetic Trip Circuit-Breaker. Air circuit-breakers with dash-pot damping are applied widely on d.c. and low-voltage a.c. circuits. Dash-pot permits closer setting for tripping current because momentary or starting current peaks will not trip breaker. Oil circuit-breakers, whose mechanisms and arc quenching principles differ from those shown, are usually applied to high voltage and high power a.c. circuits.		Addition of dash-pot on circuit-breaker delays tripping time in inverse proportion to sustained overload current. Illustrated breaker mechanism contacts cannot be held closed manually on high currents as the tripping device will operate regardless of whether breaker handle is held or is free. This mechanism is called "trip free."		
9 Thermal and Magnetic Trip Circuit-Breaker. Combined inverse time delay thermal and instantaneous magnetic trip protection is obtained by a relatively simple, low cost, and small size circuit breaker for low voltage a.c. and d.c. circuits. Frequently applied to line-starter and similar apparatus for overload and short-circuit protection and disconnect switch service. Capable of interrupting 5,000 to 10,000 amperes. Single and multiple pole assemblies are available.		Contacts are closed by handle, which is connected to moving contact by a biasing spring. Thermal overload protection is provided by bi-metal element which moves trip latch when sufficiently heated. Instantaneous magnetic trip for predetermined high currents is provided by series coil and electro-magnet. When latch is made ineffective by thermal or magnetic action, contact arm bearing moves to such a position that the contact is opened by biasing spring.		

NOTES.

10 Thermal and Magnetic Relay. Used to protect d.c. motors against overload. Delay of thermal element before opening of control contacts is inversely proportional to current for low and medium overloads of 120% or more of full load motor current. Magnetic element trips contacts instantaneously on high overload currents of 200% or higher.		Thermally actuated armature is normally held by spring and magnetic attraction of "Invar" heater carrying motor current. Heater magnetism is lost at about 465 deg. F. and armature is attracted to magnetized frame, thus opening control contacts. Separate magnetically actuated armature operates instantly on higher current. Thermal relay may be adjusted to operate at 125% to 200% above motor current. Magnetic trip may be adjusted to operate at 200% to 600% full-load current.			 Relay not applicable to A.C.
11 Transformer Type Thermal Relay. Current element withstands more severe overload and short circuit currents than some other thermal relays. Can be applied only to a.c. circuits; therefore usually built with two poles. Trips at specified value of primary ampere turns. The construction shown automatically compensates for ambient temperature.		Bimetal element is deflected upward by heat produced by secondary transformer current, which is determined by number of turns and current capacity of primary coil. Illustrated relay is compensated for ambient temperature changes by upper bi-metal element which neutralizes deflections of heated element caused by ambient temperature.			
12 Inductive Thermal Relay. Especially suitable for oil immersion. With automatic reset it should be used only for protecting low voltage protection circuits. For two-wire control circuits only the manual reset or an auto-reset relay plus a reset relay should be used, the latter serving to "lock out" the control when an overload occurs.		Copper tube inside coils and around an iron core acts as a short-circuited secondary of transformer. Heat generated in tube, which is proportional to coil current and number of turns is transmitted to bimetal element, causing it to deflect and open control contacts when damaging overloads occur.			
13 Inductive Melting Alloy Relay. Applicable only to a.c. circuits and usually has manual reset. Differs from No. 6 only in method of heating alloy metal. Relay is adjustable within certain limits for cork coil.		Heat from inductively heated copper tube is transmitted to low melting alloy around shaft of ratchet wheel. Melting of alloy at predetermined temperature produced by sustained overload current in coil permits spring to rotate ratchet wheel and open contacts. Heat generated in tube may be varied by changing position of core, thus varying the magnetic flux in the tube.			

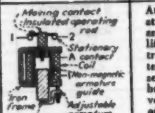
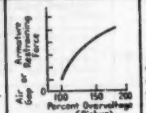
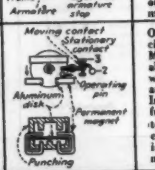
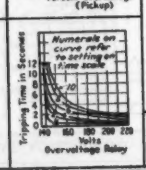
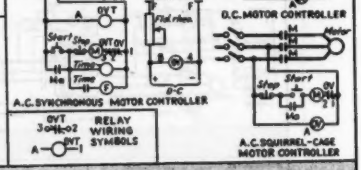
I—OVERLOAD PROTECTION (continued)

Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
14 Thermostatic Disk. Protects against over-heating of motors when caused by such conditions as too frequent starting, sustained or frequent overloads, high ambient temperature, ventilation failure or abnormal voltage. Additional overload apparatus must be used if protection is required against stalling and phase failure. Bimetallic disk is usually mounted on frame of squirrel-cage motor and on winding of synchronous wound rotor or d.c. motors. It may open power circuit by means of a contactor or close an alarm circuit.	Thermostatic Disk Applied to Squirrel Cage Motor Bimetallic disk Stationary contact Motor frame Thermostatic Disk Applied to Windings of D-C, Wound Rotor, or Synchronous Motor Steel mounting Motor winding Copper lead conducting strip	Principle explained for No. 5. Actual motor heat rather than that produced by heating coil actuates bimetallic disk. Resetting awaits cooling of motor frame or winding.	Tripping Time 0 200 400 600 Percent Full Load Amperes	D.C. MOTOR CONTROLLER A.C. SQUIRREL-CAGE MOTOR CONTROLLER WIRING SYMBOL A.C. SYNCHRONOUS MOTOR CONTROLLER

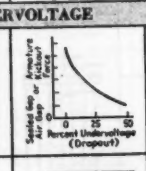
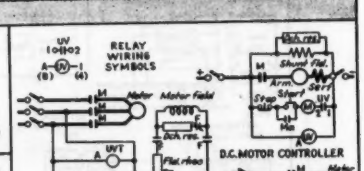
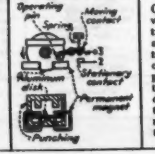
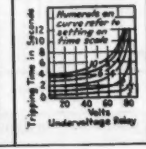
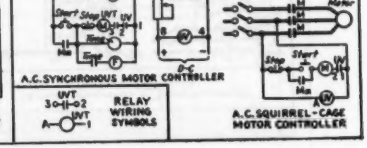
II—OVERLOAD RELAY ACCESSORIES

1 Saturating Inductive Shunt. Connected in parallel with heater of a.c. thermal overload relay to increase tripping time during starting of high inertia loads and to protect heater from high overload current. Less expensive than a current transformer.	Iron punching Winding	When thermal overload relay heater carries rated current, potential drop across heater is below saturation voltage of reactor and very small current is diverted from heater. Reactor saturates at high over-currents and a large current is shunted through it. Winding current capacity and number of turns determine rating.	Percent Heater Current 0 200 400 600 Percent Motor Current	SHUNT WIRING SYMBOL A.C. SQUIRREL-CAGE MOTOR CONTROLLER A.C. SYNCHRONOUS MOTOR CONTROLLER Shunt not applicable to D.C.
2 Saturating Current Transformer. Used to extend operating range of a.c. thermal overload relay heater, to increase tripping time, and to protect heater against high overload current.	Primary winding Secondary winding	When primary current is low, secondary or heater is directly proportional to ratio of primary to secondary winding turns. High primary current saturates iron core and ratio of secondary to primary current diminishes.	Secondary Current in % of 0 200 400 600 Primary Current in Percent of Full Load Current	TRANSFORMER WIRING SYMBOL A.C. SQUIRREL-CAGE MOTOR CONTROLLER A.C. SYNCHRONOUS MOTOR CONTROLLER Transformer not applicable to D.C.

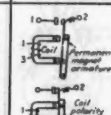
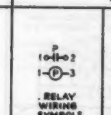
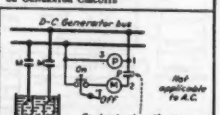
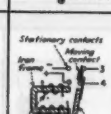
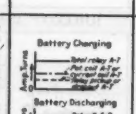
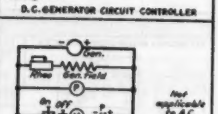
III—OVERVOLTAGE

Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
1. Instantaneous Relay. Applied to circuits and equipment where an increase in voltage over normal or rated voltage may damage electrical apparatus or affect output of driven machinery.		At normal voltages magnetic attraction between armature and frame is insufficient to lift armature and open control contacts. At a voltage determined by armature stop setting, armature is lifted to break contact circuit. This voltage depends directly upon the distance between armature and frame core.		
2. Inverse Time Delay Relay. Operates only on sustained peak voltages and will not interrupt service on momentary over-voltages. Voltage relays may be used to interlock a.c. and d.c. power supplies when both are used on the same controller. The induction type of relay is for a.c. application only.		Operates on induction principle for a.c. service only. Main potential coil is below aluminum disk. Upper two windings are energized by auxiliary coil on main pole. Interaction of magnetic fields from these coils produces torque to rotate disk and operate contacts when voltage is high. Field of permanent magnets delays disk rotation.		

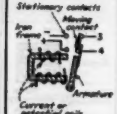
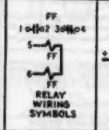
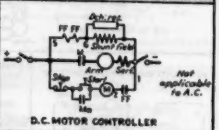
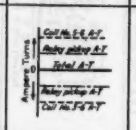
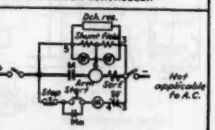
IV—UNDERVOLTAGE

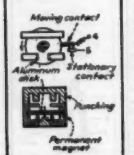
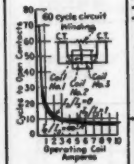
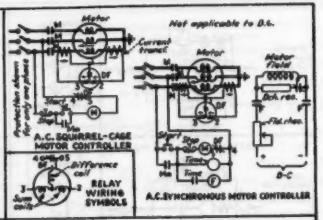
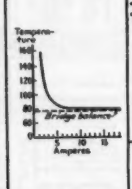
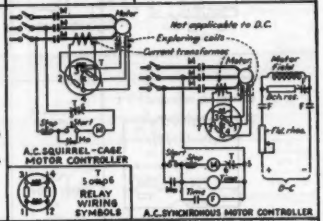
1. Instantaneous Relay. Applied to a.c. or d.c. controllers to prevent motors from operating on reduced voltage, which may affect motor speed or torque characteristics. May be adjusted to release armature, or to "drop out" at a voltage near the "pickup" voltage, at which magnetic force closes armature.		Operation is similar to instantaneous overvoltage relay but has make instead of break control contacts. Since dropout voltage is almost the same as pickup voltage, relay may be used to prevent starting or operating on a predetermined undervoltage.		
2. Inverse Time Delay Induction Relay. This relay guards against sustained undervoltages. Where circuit breakers or latched-in contactors are used, it will de-energize control circuit before voltage becomes too low to operate tripping solenoids of circuit breaker. Control circuits may be arranged so that it is impossible to start a motor unless voltage is correct.		Operation is similar to overvoltage type except for control contact. By means of slide wire resistor, disk torque may be adjusted to close control contacts at a pre-determined voltage and to release them when voltage drops. Rotation of disk, through field of permanent magnets provides inverse time characteristics.		

V—POLARITY CONTROL

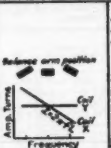
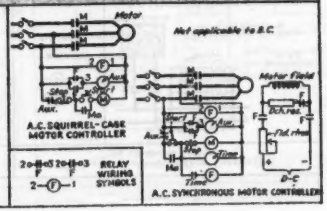
Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
1. Directional Relay. In many electro-chemical processes a reversal of current may cause damage even if the current is small or of short duration. This relay operates on voltage and can prevent energization of a load circuit if its polarity is incorrect. The relay may also be used to shut down a generator if polarity is incorrect.		Direction of current flow in coil either assists or neutralizes flux from permanent magnet. Armature is held either in attracted or repelled position depending upon coil polarity.		  D.C. GENERATOR CIRCUIT CONTROLLER
2. Current and Voltage Relay. An ordinary voltage or current relay, upon which two coils may be installed, may be used for current reversal protection. Applied to a battery charging circuit, it prevents battery discharge through generator if generator stops accidentally.		Ampere turns produced by potential coil are sufficient to operate relay. Ampere-turns produced by charging current through current coil also assist in holding relay closed. If generator voltage becomes lower than battery voltage, current reverses and tends to drive generator. Reversal of current in series coil neutralizes magnetic effect of potential coil and allows relay to open.		  D.C. GENERATOR CONTROLLER

VI—FIELD PROTECTION

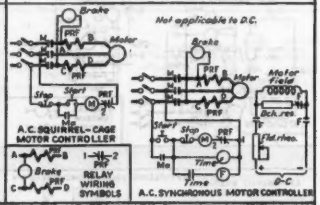
1. Field Failure Current Relay. Prevents starting or running of a d.c. motor with open field circuit since coil or coils are connected in series with motor field. On adjustable speed motors coils must be selected so that relay will operate on minimum field current and coils will not overheat on maximum field current.		Current passing through field, which is in series with coils, operates relay so that control circuit is effective. If field current fails, relay is demergized and control circuit opens.		  D.C. MOTOR CONTROLLER
2. Differential Voltage Relay. A field failure current relay will not provide protection when all or part of the field is shorted out because short-circuit current may still cause the current relay to hold circuit closed. A voltage relay used as differential relay protects against short circuit and field loss resulting from winding failure.		Voltage coils are connected across identical sections of field in such manner that magnetic force from one coil neutralizes that from the other. Armature will not move while this condition exists. If this balance is destroyed by winding failure or short-circuit, relay operates to stop motor.		  D.C. MOTOR CONTROLLER

3. Ratio Differential Relay. Protects against internal faults on a.c. apparatus by balancing current entering the apparatus against the current leaving it. Each phase has a relay. Leakage of current from one phase to another or to ground can be detected and the apparatus disconnected before serious damage occurs. Relays operate only on unbalance in the machine itself; not on system faults.		A field proportional to current in sum coils reacts with field proportional to their difference. Resultant field tends to rotate disk. Quadrature flux is supplied to upper poles by transformer windings on each of lower poles. Current through sum coils tends to hold contacts closed. A current that is proportional to load current through difference coil will open contacts. Current through difference coil is the difference between input and output currents.		
4. Winding Temperature Relay. Protects against excess heat in windings of a.c. motors. Before relay operates to stop a motor, (1) winding temperature must exceed calibrated value, (2) line current must be above normal, and (3) these two conditions must exist for a predetermined time. Relay will not operate on transient overload.		Operates on wheatstone bridge principle. Two fixed resistances in relay serve as two arms of bridge, while two copper exploring coils embedded in winding serve for other two arms. At normal operating temperature, no current flows in upper winding. If motor winding becomes overheated, bridge balance is destroyed and current flows in relay upper winding. Field thus produced by upper winding reacts with that of lower winding and produces a torque to rotate disk to stop motor.		

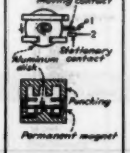
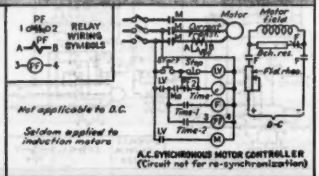
VII—FREQUENCY CONTROL

1. Frequency Relay. Prevents operation of induction or synchronous motor on higher or lower than normal frequency, which is proportional to motor speed.		As long as frequency for which relay is set remains constant, balance arm does not move. A change in frequency changes impedance of inductance coil and destroys magnetic balance, since any frequency change has relatively little effect on resistor circuit.		

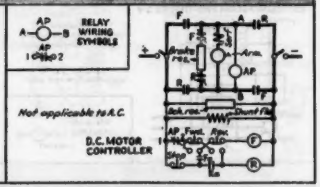
VIII—PHASE REVERSAL OR FAILURE

Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
1. Phase Reversal and Phase Failure Relay. Prevents (1) change in direction of a.c. motor rotation and (2) operation on single phase. Reversal of phase rotation in a polyphase system reverses motor rotation. Failure of one phase would compel a motor to operate on single phase, with probable excess current and resultant overheating.		Operates on same principle as two-phase induction motor. Eddy currents induced into aluminum disk react with rotating field to produce a torque. Disk tends to rotate and holds contacts closed if line phase rotation is correct. If a line phase opens when motor is running, spring force opens relay contact because single phase develops no torque. If phases become reversed, disk rotates to stop motor. If phase rotation is altered, a motor being started will run only an instant until relay operates.		

IX—POWER FACTOR

1. Power Factor Relay. Opens circuit and stops motor or re-synchronizes synchronous motor when power factor of a.c. circuit drops below predetermined value. Principal application is to synchronous motor controllers. Provision must be made on controller to make relay ineffective during starting period as power factor is very low		When voltage and current are in phase, their magnetic fields produce no torque to rotate aluminum disk. Torque from the two fields is proportional to their product times the sine of the angle between them. Relay may be calibrated to operate at 80% lagging power factor.		

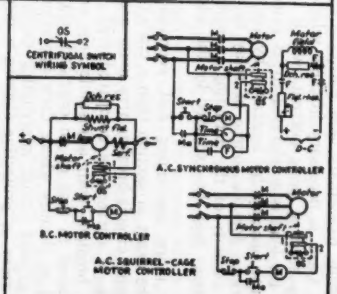
X—ANTI-PLUGGING

1. Anti-Plugging Voltage Relay. Prevents closing contacts in motor reversing controllers to reverse direction of d.c. motor rotation until the rotating armature has been braked down to safe speed. On high inertia loads anti-plugging control prevents excessive strain on motor and driven machinery. Relay is so designed that it will not close its contacts until armature of motor has practically stopped rotating.		Relay has high pickup ampere-turn and low dropout ampere-turn characteristic. When motor is connected to normal voltage, relay contacts are open. They remain open until generated armature voltage falls below a critical value. These characteristics are given by a large armature gap and a small permanent gap in relay magnetic circuit.		

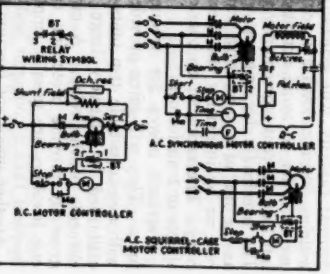
NOTES.

XI—PLUGGING
XII—SHORT CIRCUIT
XIII—FLASHOVER

XIV—OVERSPEED

Type and Application	Mechanical Construction	Principle of Operation	Typical Operating Curves	Typical Applications to Motor Controllers or Generator Circuits
1. Centrifugal Switch. Prevents overspeed of motor or may be used as a governor. Actuates control equipment to maintain constant speed of rotation. Often used to maintain constant speed on universal or series motors applied to business machines.		Contacts remain closed as long as spring pressure exceeds centrifugal force when device is rotated. Speed at which contacts open may be adjusted by spring or by varying mass of moving contact. Slip rings connect rotating mechanism to circuit.		

XV—BEARING TEMPERATURE

1. Thermostatic Relay. Protects bearings, resistors, cables, transformers, etc. against overheating. Thermostatic bulb may be located in material or in contact with material to be protected. Where equipment for supervision, relay usually actuates a signal to prevent unnecessary shut downs. Where supervision is not maintained, relay may be used to stop motors.		When temperature of material to be protected rises, liquid in connecting bulb volatizes and creates pressure which expands bellows operating toggle mechanism.		

protection may be obtained in two ways—by limiting the motor temperature directly or by means of an external current relay which has a thermal characteristic proportional to that of the motor.

Thermal overload relays are suitable for most applications because their thermal capacity will generally permit momentary and harmless overloads without shutting down a machine. Care is necessary in their selection and use in order to avoid actuation by starting peak current, which is above full load current momentarily until the load is accelerated to its rated speed. The overload relay tripping time can usually be increased by such means as the use of a saturating transformer for the source of relay heater current or by increasing the thermal capacity of the actuating member of the relay. The rating of an overload relay may be extended by the addition of shunts or transformers.

Overload relays are frequently more convenient and economical than fuses. They will often provide more exact protection than a circuit breaker with non-adjustable trip units because circuit breaker trip units are usually calibrated in relatively large units of current as compared with the trip elements of the relay. A circuit breaker with adjustable trip units will generally provide protection equivalent to that of an overload relay. Circuit breakers are usually employed in circuits where their operation is less frequent than a contactor and for greater circuit interrupting capacity.

Another important function of a relay or protective element is circuit protection. Relay operation serves to sectionalize and disconnect an abnormal or disabled circuit automatically so as to prevent stoppage in other essential circuits. Disconnection is usually fast enough to prevent serious damage to the apparatus and production delays.

Other relays may function as the detector of a control system and may act with or without delay to effect the right sequence of operations. Relays with time delay operation usually discriminate between harmless momentary and dangerous sustained abnormal conditions. Additional data on time delay relays were published in "Product Engineering," February, 1942, pp. 86-88. A relay is much more efficient and positive in operation than human manual control because it does not have the frailty of forgetting and is always prepared to act.

TRANSMISSION OF POWER IN COMPRESSED GAS ATMOSPHERE.

This abstract was prepared from a paper by Henry M. Hobart, published in the September and October, 1942, Journal of the Franklin Institute.

The Purpose of the Present Article.—This article constitutes an attempt to advance, by library research, interest in utilizing compressed gases for insulating purposes as alternatives to, or in combination with, the dielectric materials now commonly employed.

Although a limited amount of laboratory research in this field, already is available, and further researches are in progress, practical applications of great present value still are receiving insufficient attention because of the dearth of basic information derived from careful laboratory tests. It is hoped that this library research article may lead to increased interest and the undertaking of much needed further laboratory research on the dielectric characteristics of compressed gases.

The present writer's study of the subject of the dielectric characteristics of compressed gases has convinced him that (1) a 60-cycle underground (or

surface) transmission system for very high voltage and employing compressed gas as insulation, and (2) compressed gas power transformers, will constitute two important engineering applications. Ultimately they will be widely employed for power transmission and for power pools, and will be accompanied by great economies and operating advantages.

Quite aside, however, from these two projects, it appears timely to have available in a form adapted to serve engineering purposes, some basic data of the insulating properties of compressed gases. The existing data of the subject are meager, often inconsistent, and widely scattered. It needed discriminative checking and coördinating in order that it may be utilized effectively by engineers.

In the course of this coördinating task, it was inevitable that the writer should learn of many phenomena which are in need of further laboratory research before they can be taken into account with the degree of certainty essential to obtaining the best results. If that is done, then, irrespective of whether the results reveal faults or advantages, the way will be cleared for many useful new applications of compressed gases in various kinds of machinery, not only on account of their insulating properties, but also for heat-transfer and other purposes.

Fundamental Dielectric Data of Compressed Gases.—The curves in Figure 1 show the breakdown strengths of several gases when compressed to 20 and 40 absolute atmospheres (ata), for sine-wave voltages of usual periodicities (50 and 60 cycles). The ordinates are crest volts per mil and the abscissæ are spacings in mils. The electrodes employed were of such shapes and dimensions as to decrease the non-uniformity of the field for the spacings employed. The curves are of the nature of composites made up from various published reports of laboratory researches which bear the evidences of earnestness and skill on the part of the researchers. Comparatively few of these researches included simultaneously, high compressions, great spacings, and very high voltages.

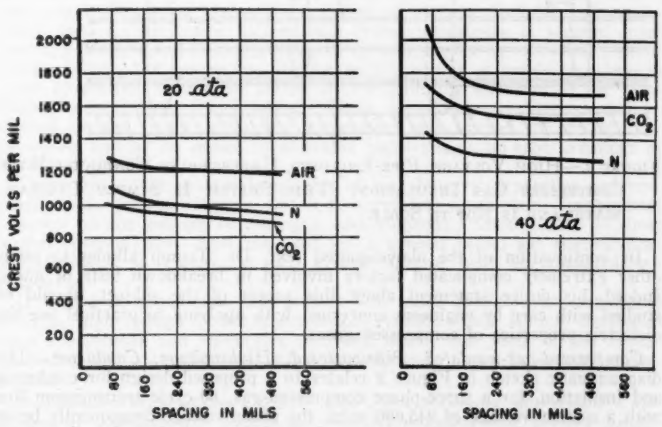


FIGURE 1.—CREST BREAKDOWN STRENGTH OF AIR, NITROGEN AND CO_2.

Although there were many unaccountable and often considerable differences in the results examined, these composite curves are reasonably adequate to serve as bases for the engineering-estimate purposes of the present article.

As only one out of the many examples which could be cited with respect to the inevitableness of considerable deviations due to the particular conditions applying to each research, it is of interest to quote from a statement by Dr. J. G. Trump, published at p. 676 of Vol. 60 (1941) of the "A. I. E. E. Transactions" (see June 1941 "Supplement to Electrical Engineering Transactions Section"), as follows: "We have observed that the maximum voltage which can be readily obtained under given conditions of pressure and field geometry, is less when the area of the electrodes is large. This is probably caused by the increased difficulty of approaching ideal conditions over large areas. It may be estimated that the effective area of our inter-electrode gap was about a hundred times that of Prof. Skilling. Considerations such as these must be taken into account by engineers interested in applying to large apparatus, high-voltage data taken on small electrodes."

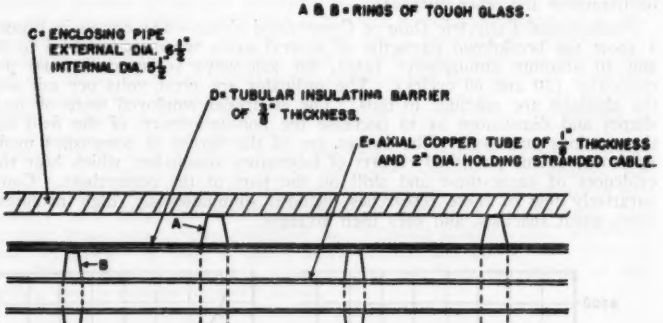

A & B = RINGS OF TOUGH GLASS.
C = ENCLOSING PIPE
EXTERNAL DIA. 9½"
INTERNAL DIA. 8½"
D = TUBULAR INSULATING BARRIER
OF ¾" THICKNESS.
E = AXIAL COPPER TUBE OF ½" THICKNESS
AND 2" DIA. HOLDING STRANDED CABLE.
A
B

FIGURE 2.—HIGH VOLTAGE, PIPE-ENCLOSED, UNDERGROUND CONDUCTOR WITH COMPRESSED GAS INSULATION. THIS SKETCH IS SIMPLY DIAGRAMMATIC AND IS NOT TO SCALE.

In continuation of the above-quoted text, Dr. Trump alludes to many other extremely complicated factors involved in breakdown tests of gases. Indeed, his entire statement about this aspect of the subject, should be studied with care by engineers concerned with applying to practical use the dielectric properties of compressed gases.

Compressed-gas-insulated, Pipe-enclosed, High-voltage, Conductor.—The diagrammatic sketch in Figure 2 relates to a proposed design for conductor and insulation, for a three-phase compressed-gas, 60-cycle transmission line with a system voltage of 345,000 volts, the phase voltage consequently being 200,000 volts. Between the inner surface of the enclosing pipe C and the outer surface of the axial copper tube E (which may alone constitute the conductor, or may be reënforced by containing a stranded conductor), the

stress in service corresponds to the phase voltage of 200,000 Rms. volts or 283,000 crest volts. The radial spacing between the 2-inch diameter conductor E and the enclosing pipe C is 1¼ inches. Thus the average gradient for the entire gap is (283,000/1750 =) 162 crest volts per mil. Later in this article, it will be shown that the voltage-stress at the surface of the conductor E, is, in service, 280 crest volts per mil, and we must provide a gas and a degree of compression which will correspond to a suitable factor of safety when withstanding this stress.

Voltage stresses of this order of magnitude are already employed in service in the insulating wall of a type of high-voltage underground cable which is provided with a filling of thin, degasified oil for impregnating the paper insulation on the conductor. Such cables are provided with external means for maintaining the oil under a low pressure of the order of 15 to 25 pounds per square inch to prevent void formation within the confines of the sheath. The original of this type of cable was devised in Italy by the firm of Pirelli. Although these cables are excellent, their cost per mile is several times greater than the cost of *overhead* transmission lines for the same voltage and power. Their use, consequently, is limited to relatively short distances, and for locations where *overhead* lines would not be permitted. The highest voltage for which such cable has yet been employed, corresponds to a system voltage of 220,000 volts and a phase voltage of 127,000 volts.

The example of a 345,000-volt line (corresponding to the dimensions on the sketch in Figure 2), was purposely taken for illustrating the system described in this article, since while 345,000 volts is believed to be much lower than voltages attainable with a compressed gas design of the kind which will be described, it is well above present proven practice, not only for underground cables but for overhead transmission lines.

It is, however, believed that the proposed high-voltage, compressed-gas, 60-cycle system is not only of superior value for the transmission of large amounts of power to great distances, but that it will be of *lower cost* than *overhead* transmission lines of equal reliability, and will be much cheaper than any *underground* high-voltage system at present available. If exclusively used for an entire high-voltage system, immunity is secured from lightning damage and lightning outages. If it is applied to *extending present* overhead lines, the system has features which permit of providing adequate surge attenuation before the arrival of the lightning transient at the step-down compressed-gas transformers. These step-down transformers will be entered through pipes containing compressed gas instead of through the expensive, and by no means invulnerable high-voltage, oil-type, bushings at present employed.

There still is but meager knowledge of the dielectric properties and propensities of compressed gases, and it is urged that much more fundamental research on the subject be promptly and vigorously undertaken. If these further investigations show the need for a greater radial gas spacing than that indicated in Figure 2, such greater spacing will be employed and vice-versa.

It should be noted that this project will make available an economical 60-cycle high-voltage power-transmission system which is not dependent upon conspicuous and vulnerable overhead lines. All parts of the system (including the compressed-gas power-transformers), may be located underground.

Preliminary Application Tests of this System Should not Await Completion of Fundamental Researches.—Notwithstanding the present insufficiency of our knowledge in the field under consideration (use of compressed gas as insulation), it is believed that with careful liberality in the proportion-

ing of the parts required, we already know enough of the subject to justify going ahead vigorously with an actual trial design which should be placed in service as a branch or extension of some already-existing system. If such an experimental branch line is shown to be satisfactory, and if the superiority in performance, and the saving in cost are as great as has appeared from careful study to be quite certain to be the case, it is only reasonable to anticipate the wide use of the system in the contemplated early expansion of the nation's electric power facilities.

Finkelmann's Researches on Compressed-gas Dielectrics.—Some researches reported by Finkelmann at pp. 282 to 286 of Vol. XXXI (1937), of "Archiv für Elektrotechnik," included measurements of the breakdown strength of several gases for the very non-uniform field conditions between concentric-cylindrical electrodes, as compared with their breakdown strengths between parallel-plate electrodes, providing a fairly uniform field. In the case of the concentric-cylindrical electrodes, the inner diameter of the outer cylinder was about 8 inches ($d_1 = 8000$ mils). Tests were made with four inner cylinders whose outer diameters were respectively about 7200, 6400, 5600 and 4800 mils. The corresponding spacings thus were about 400, 800, 1200 and 1600 mils. The largest of these spacings (1600 mils) is seen to be not much different from the design in Figure 2 (where the spacing is 1750 mils). But Finkelmann's inner cylinder for that spacing was of about 4800 mils outer diameter, whereas the outer diameter of the conductor in Figure 2 is only 2000 mils. This difference prevents drawing more than very rough conclusions.

An additional difference between Finkelmann's condition and ours, relates to the use of a much higher compression (50 ata) in the case sketched in Figure 2, instead of the compressions extending up to only half that amount, used in Finkelmann's research. No alternating-voltage test results for the dielectric strength of CO_2 gas at as high a compression as 50 ata, associated with so great a spacing as 1750 mils and between concentric cylinders, appear to be available.

The curves in Figure 3, for concentric-cylinder gaps, represent the next step in our library research. The 10 ata and the 20 ata curves are obtained quite directly from the data in the Finkelmann publication. By reasonable extrapolation and from analogy with other available data, the 30 ata and 50 ata curves (at the right-hand side of Figure 3), have been constructed.

In the curves of both Figure 1 and Figure 3, interest attaches to the great changes in the relative shapes and values for the different gases. On the basis of the data at present available, Figure 2 appears to represent a reasonable basis for consideration. The project presents such great advantages as to justify a pipe design employing a considerably greater diameter and, consequently greater cost, if further investigations show it to be desirable.

The curves in Figures 1 and 3 show us that both for plane gaps and for concentric-cylinder gaps, nitrogen becomes increasingly inferior to the other gases examined, the greater the compression employed, and that for large spacings in the concentric-cylinder tests, nitrogen shows up particularly badly. Thus we are tempted to turn our attention to alternatives, such as air and carbon dioxide.

Zeier's Researches on the Dielectric Properties of Compressed Gases.—An interesting comparison between the dielectric strengths of air and nitrogen is found in a test made by Zeier ("Annalen der Physik," 14, p. 433, 1932). At a compression of 40 ata, and employing a 20-mil spacing between two spheres of 15 millimeter diameter, Zeier measured the breakdown voltage for pure nitrogen gas. Then Zeier gradually replaced the nitrogen by air, measuring the breakdown voltage at each increase in the amount of air. For 100 per cent air, the dielectric strength was about 18.5 per cent greater than for

FIGURE 3.—DIELECTRIC STRENGTH FOR VARIOUS SPACINGS AND COMPRESSIONS OF AIR, NITROGEN AND CO_2, IN FIELDS BETWEEN CONCENTRIC CYLINDERS.

100 per cent nitrogen. Zeier furthermore noted the important phenomenon of a gradual decrease in the "spread" or "scatter" in the observed values with increasing proportions of air. If we neglect the fact of the presence in air of small amounts of other gases and simply consider its nitrogen and oxygen content, we must attribute to the 21 per cent of oxygen corresponding to the "all air" condition, the great increase in the dielectric strength as compared with "all nitrogen." The tests were made with direct current and the results are tabulated below.

Notes.	Nitrogen.	Oxygen.	D.C. Breakdown Voltage.	Crest, Volts per Mil.	"Spread" in Observed Values.
All Nitrogen	100%	0	49,000	2,440	4.5%
	95%	5%	53,800	2,690	1.7%
	90%	10%	55,000	2,750	1.4%
	85%	15%	56,500	2,830	1.1%
	80%	20%	57,500	2,880	0.8%
All Air	79%	21%	58,000	2,900	0.7%

The "spread" in the values observed for the breakdown voltage, is an important factor in judging of the dielectric suitability of a gas. It is interesting to notice that in the Zeier test, the addition to the nitrogen of only a few per cent of oxygen, halved the "spread." It is well known that at atmospheric pressure, the presence of an exceedingly small quantity of CCl_4 vapor in air, *doubles* its dielectric strength. Thus it appears that in gases, just as in solid and liquid materials, there are evidences that the merest trace of some foreign substance may exert an utterly disproportionate influence on some important property of a gas. Facts of these kinds indicate that careful study should be given to the possibilities of greatly improving the dielectric properties of gases by adding small but appropriate foreign ingredients. Similarly, the removal of even very slight quantities of an undesirable ingredient, reasonably may be expected to effect well-worth-while improvements. Some researchers have observed that very slight impurities in electrode materials, and even mere surface contaminations of the electrodes, have exerted surprising effects on the values obtained for the breakdown voltages.

Some Tests With Different Electrode Materials.—At p. 114 of the March, 1941, issue of "Transactions A. I. E. E.," Skilling and Brenner report results obtained by them for the breakdown strength of air with spacings of 50 mils and less, and a compression of 20 ata, between brass and steel spheres. With the steel spheres, the breakdown srengths were some 10 per cent to 15 per cent greater than with the brass spheres. Goldman (p. 91 of "Comptes Rendus de l'Academie des Sciences de l'U.R.S.S.," 1938, Vol. XVIII, No. 2), investigating the breakdown strength of nitrogen over a wide range of compressions, found that for a spacing of 0.4 mil between a 20 millimeter diameter steel sphere and a 50 millimeter diameter flat disc, the 50-cycle breakdown voltages were 8 per cent to 10 per cent higher with a chemically-pure aluminum disc than with a brass disc.

Comments on Air, CO_2, and Nitrogen.—Finkelmann cites as disadvantages of air, (1) "the danger of ozone formation" and (2) "the precipitation of deposits on the electrodes," which suggests a proneness to electrode-surface contamination. With regard to CO_2, Finkelmann states that "it should be noted that CO_2 may be more readily obtained free from dust particles and traces of moisture than is the case with nitrogen." He continues by stating that the "scatter" of the values of the breakdown voltages

is far less for CO_2 than for nitrogen. In this respect of the considerable "scatter" of the breakdown values in nitrogen, we thus find agreement with Zeier.

Taking advantage of these opinions, the next steps in the comparison between plane and concentric-cylindrical electrodes, are limited to CO_2. In Figure 4, the three upper curves represent compressions of 30, 40, and 50 ata and moderately uniform fields, such as the fields between spherical electrodes of large diameter as compared with the spacing. The three curves are in part plotted from values estimated by extrapolation from tests at lower compressions. There have, however, been taken into account some results published by Zeier in 1932 for CO_2, small spacings, and 50 ata compression. The uppermost curve in Figure 4, which is for CO_2 at 50 ata, is believed to be amply correct for use in engineering applications.

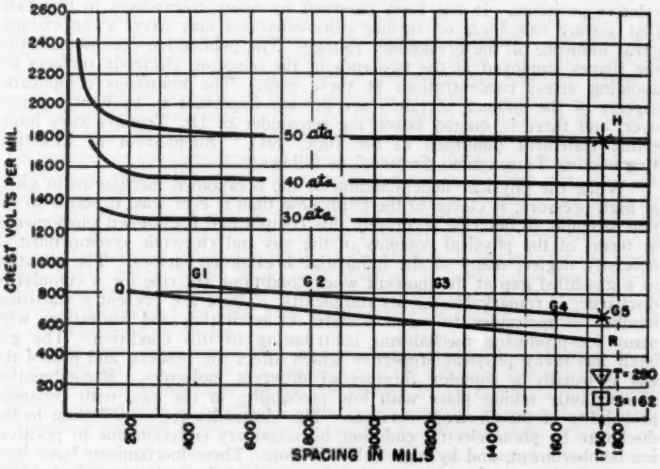


FIGURE 4.—DIELECTRIC STRENGTH OF CO_2 GAS FOR VARIOUS SPACINGS AND COMPRESSIONS. IN UNIFORM AND NON-UNIFORM FIELDS.

The Gradient at the Conductor Surface.—In Figure 4, the line QR for the average breakdown strength in crest volts per mil at 50 ata for concentric-cylindrical electrodes, is similarly deduced (i.e., from the curves of Figure 3). The values designated G1 to G4 are obtained in each case by adding to the QR values, the gradients at the surfaces of Finkelmann's four inner cylinders for the four corresponding spacings of 400, 800, 1200, and 1600 mils. These are the spacings which were employed by Finkelmann in concentric cylinders, but with much lower compressions. The four surface-gradient values, G1 to G4, thus calculated, are: 810, 771, 720, and 677 crest volts per mil. They provide a line passing through the points G1 to G4. These G points represent the breakdown crest volts per mil at the conductor surface for the four sets of Finkelmann electrodes, which would have been observed if the CO_2 tests had been made at a pressure of 50 ata instead of at the much lower pressures used in his laboratory research.

Examination of Figure 4 indicates that in the relatively non-uniform gap between two concentric-cylinder electrodes, the compressed gas breaks down at much lower average stresses (expressed in crest volts per mil) than in a gap of the same spacing, between plane electrodes. Furthermore, it appears that the conductor-surface curvature accounted for but a small part of the decrease in the breakdown voltages below the values corresponding to the relatively much more uniform conditions in gaps between plane electrodes.

To what cause or causes are we to ascribe the large remainder of the total decrease? Some of the decrease is due to the considerable departure from field uniformity inherent to the case of gaps between concentric cylinders. Probably a part is due to the effect observed by Dr. Trump corresponding to the relatively-much-greater electrode surfaces in the concentric-cylinder tests than in the plane-electrode tests. Possibly there was a lack of perfect symmetry in their geometry or in the geometry of their precise relative positions. It has been observed by many researchers in this field, that *surface roughness* or *surface contaminations* may exert a surprisingly great influence on the breakdown voltage. The publication does not mention the shapes employed at the two ends of the opposing electrode surfaces for avoiding stress concentrations at these ends. The numerous complicated aspects of the subject, certainly are far too important to be lightly passed over, and there is quoted below the remainder of Dr. Trump's very interesting statement published in the June, 1941, "Supplement to Electrical Engineering Transactions Section," as follows:

"While the physical understanding of the breakdown mechanism in gases at high pressure, is closer to the truth now than it ever was, it seems to me that attempts to describe accurately this complicated breakdown phenomenon in terms of the physical contents of the gas and electrode system, must of necessity neglect many of the influential breakdown factors. The situation in a gas-filled gap at the moment when conditions are ripe for a cumulative discharge, is remarkable for its complexity. There are present a statistical number of molecules in various states of excitation and ionization, with many ion-producing mechanisms contributing to this condition. The gas itself has many physical properties which affect the process, and indeed the gas is usually a complex mixture of different molecules. Recombination is constantly taking place with low probability in the gas, with enhanced probability at the electrode surfaces. The electrodes are contributing to the discharge by photo-electric emission, by secondary emission due to positive-ion bombardment, and by high field-emission. These mechanisms have been quantitatively examined separately, by careful physical research in high vacuum with thoroughly out-gassed electrodes. In a gas-filled gap these mechanisms are taking place together. The electrode surface is covered by many molecular layers of contaminated material which obscure the emission characteristics of the metal itself. The electric field which may be uniform or of some other geometry because of the shape of the electrodes, is profoundly affected by both the general space charge in the gap as a whole and by the dynamic localized space charge concentration in the region of electron avalanches. The gap is being irradiated by radiations from natural radioactive materials and by cosmic rays. In spite of this complexity, it is possible and desirable, to understand the rôle which the various processes play in the general picture of breakdown and many valuable contributions to this phase of the insulation problem have been and are being made."

Stress Concentrations in Gaseous Dielectrics.—A study of the above quotation leads the engineer to recognize in particular an important fundamental property of gaseous dielectrics, which is not present in nearly as intense degree in liquid or solid dielectrics. This relates to the great electronic mobility of gases. Microseconds are sufficient, in the case of gases, for

electronic stress concentrations to shift their location and also to greatly change their intensity.

Dependence of Breakdown Voltage on Gas Mobility.—At a couple of places in Zeier's research report entitled "Durchschlaguntersuchungen in Komprimierten Gasen und in Flüssiger Kohlensäure" ("Annalen der Physik," 14, 1932, pp. 415 to 447), allusion is made to the influence of gas mobility and the possibility of increasing the dielectric strength by circulating the gas instead of letting it remain stationary. Reasons are given why this might be effective, and references are made to trends noticed in certain researches.

If the breakdown voltage can be increased by circulation of the gas, it should be given consideration for our pipe-enclosed, compressed-gas, power-transmission system. It will also provide an alternative means of obtaining automatic control of the temperature of the gas.

Zeier's article also contains allusions to the fault of particular gases (nitrogen especially) of experiencing a decrease in dielectric strength with increasing compression as the result of the attendant decreased mobility. Zeier points out that any cause which decreases the mobility, tends to lower the rate of increase of the breakdown voltage. Adequate circulation of the gas, conceivably may much more than restore the decrease in mobility occasioned by the increased compression.

Returning to the consideration of the curves in Figure 4, the next step in our library research consists in extending the G1, G4-line out to a gas spacing of 1750 mils, which is the spacing shown in Figure 2, between the outer surface of the 2-inch diameter conductor and the inner surface of the enclosing pipe. Designating by G5 the 1750-mil point on the extension of the G1, G4 line, we obtain the result of 650 crest volts per mil for the breakdown value which would have been obtained if Finkelmann had tested a fifth concentric-cylinder assembly with $d_1 = 8000$ mils, d_2 (the diameter of the inner conductor) $= 4500$ mils, spacing $= 1750$ mils, and using CO_2 gas at a compression of 50 ata.

Already we have noted that in the design sketched in Figure 2, for $d_1 = 5500$ mils, $d_2 = 2000$ mils, spacing $= 1750$ mils, the average crest volts per mil for the stress with our system voltage of 345,000 volts, corresponding to a phase voltage of 200,000 volts, is 162 crest volts per mil. The corresponding gradient at the conductor surface is 280 crest volts per mil.

That is to say: the surface voltage gradient for our 2-inch diameter conductor inside the 5½-inch internal-diameter pipe, is, in service, 280 crest volts per mil.

If, as a rough approximation, we can properly apply the Finkelmann data to considerably different diameters for a given spacing, then, basing our estimates in other respects, on the Finkelmann research, we find that for CO_2 gas at a compression of 50 ata, and a spacing of 1750 mils, the breakdown voltage gradient at the surface of the 2-inch diameter conductor shown in the sketch of Figure 2, will be 650 crest volts per mil, corresponding to the point G5 in Figure 4. This is $(650/280 =)$ 2.32 times greater than the stress of 280 crest volts per mil to which the gas at the conductor surface will be subjected *in service* with a phase voltage of 200,000 Rms. volts between the conductor and the enclosing pipe.

In Figure 4, there is denoted by H, the breakdown strength in CO_2 gas for the field between plane electrodes, a compression of 50 ata, and a spacing of 1750 mils. The ratio of H to G5 is $(1780/650 =)$ 2.74.

The roughly-estimated stresses to which the conductor may be subjected in actual service with 200,000 phase volts between the conductor and the enclosing pipe, are:

162 average crest volts per mil for the whole gap, as plotted at S in Figure 4, and:

a gradient of 280 crest volts per mil at the conductor surface, as plotted at T in Figure 4.

S (162 crest volts per mil) = 32.5 per cent of R.

T (280 crest volts per mil) = 43.0 per cent of G5.

It is of interest to note that the ratio of the relatively much more uniform field breakdown strength at point H in Figure 4, to the values of S and T respecively, are:

$$H/S = 1780/162 = 11.0$$
$$H/T = 1780/280 = 6.3.$$

A hasty consideration of these ratios, for H/S and H/T, evidently would lead to dangerously optimistic conclusions. We have seen that closer examination indicates that the actual margins of reserve dielectric strength are much less.

We have in reserve the employment of gases of greater dielectric strength than those as yet considered in this article, and the use of higher compressions. As may be seen from the curves in Figure 5, for crest volts per mil versus compression (for a 500-mil spacing), the slope of the carbon dioxide curve is still quite steeply upward where it crosses the air curve at 50 ata. This would suggest increasing the compression of CO_2 to 60 ata, or even more, for use for insulating the pipe-enclosed conductor.

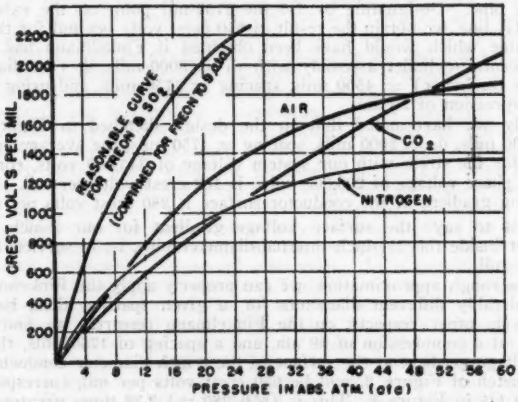


FIGURE 5.—60-CYCLE DIELECTRIC STRENGTH OF SEVERAL GASES FOR A 500-MIL SPACING, AS A FUNCTION OF THE COMPRESSION.

Some of the Advantages of the System.—This pipe-enclosed, compressed-gas-insulated, high-voltage, 60-cycle, transmission conductor, when successfully developed, will have advantages of much importance. It will serve the purposes for which 60-cycle, high-voltage, overhead lines are now employed. It provides immunity from outages due to lightning storms, and

from breakage of cables from accumulations on the cables of ice and sleet and by wind stresses. It decreases dangers to and from air traffic. It decreases interference with communications systems. In war time, there is less exposure to enemy depredations, and consequent outages. The dielectric constant of gases being unity, the use of compressed gas as insulation, will greatly decrease the capacitance, as compared with underground cables employing solid materials or oil for their insulation. This much lower capacitance will decrease the cost of providing the necessary compensation.

Cost comparisons yield results which are decidedly favorable to this type of high-voltage transmission line. It will be cheaper than first-class overhead lines, and the comparison becomes rapidly more favorable to the compressed-gas, pipe-line system, the greater the amount of power per circuit, and the higher the system voltage employed.

Direct-current Transmission.—Some engineers maintain that d.c. transmission will be still more effective than the 60-cycle system. Future developments are likely to show this to be the case. Even with present relatively inexpensive "solid filled" paper cable, the use of d.c. is practicable with insulation stresses in the dielectric, several times greater than can be withstood by such cable during years of service-subjection to 60-cycle stresses. Thus, so far as relates to the transmission line itself, the use of d.c. will permit of the *economical* provision of *underground* high-voltage transmission of large amounts of power to great distances, and of thus avoiding the many disadvantages of overhead transmission.

With the compressed-gas type, it is also true that the d.c. conditions are more economically met than are 60-cycle conditions, and careful comparisons show that the compressed-gas transmission conductor's cost is, for direct-current, roughly only a matter of half its 60-cycle cost for a given high-voltage transmission application.

But taking into account as we now find them, the other factors in the d.c. versus 60-cycle high-voltage transmission situation (and particularly the vast sums already invested in 60-cycle installations), the right course at the present time, is believed to be that of building 60-cycle, long-distance and power-pool systems which will not require overhead conductors.

Historical Note.—Before concluding these considerations regarding d.c. transmission, let us again recall to our minds the late M. Réné Thury's splendid pioneering achievements in d.c. transmission using constant current instead of constant voltage. Thury's work was seriously handicapped by the sparseness of the loads in those early days, due to the slowness of the development of electrical methods and machinery. With the present enormous demands for electric power, Thury, employing practically all his original plans, certainly could have achieved great success with his system.

Making the first large-scale application to power-transmission purposes, of the developments in electronic engineering, and retaining the advantages of the constant-current feature in the transmission line, the late Mr. C. W. Stone, in the face of all kinds of discouragements, carried through to complete success, the design, construction and commercial operation of a transmission system, which, starting at Mechanicsville with three-phase, 40-cycle generated power at a constant potential of 10,500 volts, converted it to constant current by means of a Boucherot circuit, and then rectified it in phanatron tubes. The direct current, which had a constant value of 175 amperes, was then transmitted 17 miles by an overhead line to a terminal station at the Schenectady Works of the General Electric Company where it was inverted in thyratron tubes, and then converted to constant-voltage 60-cycle three-phase power in another Boucherot circuit. In that form, part of the power was used in the factories of the General Electric Company, and the rest was delivered into the Schenectady network of the New York

Power and Light Corporation. At the rated load of 5280 kilowatts, the direct-current potential was 30,000 volts.

This interesting and epoch-making transmission system was the first American example of the use, for power transmission, of direct current of constant value, and with the voltage varying with the load. The system gave entirely reliable service and some 50 million kilowatt-hours were transmitted by it in its first two years of commercial operation. The system was placed in service in August, 1936.

Sixty-cycle Transmission.—So far as regards the project described in this article, it is limited to the advocacy of the 60-cycle, pipe-enclosed, underground or ground-level, high-voltage, compressed-gas system. The overhead line typical of present high-voltage long-distance transmission practice, has extremely high first cost at 286,000 volts, the highest system voltage yet employed. It is believed that any higher voltage with the present overhead system will be associated with much greater first cost, and will present increased operating difficulties. But with the compressed-gas pipe-line system, studies indicate that even half-a-million volts will not constitute an upper limit, either for the line or for the step-down and step-up compressed-gas transformers which constitute an important part of the system. Engineers will thus be free to employ any voltage indicated by the economics associated with the required amount of power per circuit and the transmission distance.

Temperature Considerations.—As to the particular gas to be employed, nitrogen is inferior to CO_2 in several important respects. It may be objected that since the critical temperature of CO_2 is 31 degrees C., trouble will be encountered due to condensation when lower temperatures occur, since we are proposing to use a compression of some 50 ata. This objection may be met by arranging in any one of several simple ways, that the temperature of the gas inside the pipe always shall be maintained at a reasonable margin above 31 degrees C., say, around 36 degrees C. For a 60-cycle transmission line, a particularly appropriate procedure will be to thermostatically control the degree of phase compensation. Our conductor, within its enclosing pipe, is characterized by having rather high capacitance, notwithstanding that gases have unity dielectric constant. In order to keep down to a reasonable amount, the leading component of the current in the conductor, various ways of providing for an increase in the inductive loading may be employed. Some of these ways readily adapt themselves to permitting automatic adjustments of the inductive component of the current in the conductor, and hence also of the I^2R loss per unit length of the conductor. In this way, we can automatically control the temperature of the CO_2 (or other gas) within the pipe, without changing the amount of power (i.e., the "in-phase"), component of the load on the system.

Capacity-current Compensation.—At p. 10 of the January, 1934, issue of the (British) "Journal of the I. E. E.," in discussing underground paper cables, Mr. P. V. Hunter makes the following comments regarding capacitance compensation:

"It seems probable that the resultant cable will require some measure of compensation for capacity current, when operating with alternating voltages of 132 Kv. and higher. This has been investigated in a preliminary way, and it appears that the most convenient method is to increase the magnetizing current of the step-down transformers, as this is cheaper than to provide special reactance equipment."

From a note dealing with the subject of "Cable-Capacitance Compensation" at p. 259 of the July, 1941, issue of the (British) "Journal of the I. E. E.," Part I, the following quotation is of interest:

"On the Paris 220-Kv. system, the step-up transformers are fitted with a tertiary delta 11-Kv. winding to which one or more shunt reactors may be connected at will by switchgear. The generators and transformer primary windings may thus operate at nearly unity power factor."

In present-day underground paper-cable practice, we have to severely restrict the cable's operating temperature in order to preserve the good condition of the paper insulating material, and thus lengthen the cable's life. This necessary concern for the life of the cable, often requires the provision of much larger and more expensive cables than otherwise would be needed. But in the compressed-gas alternative, so far as regards any concern over deterioration of materials, we are free to permit any desired operating temperature.

Constant-temperature Operation Eliminates Need for Expansion Joints.—There is a further important consequence of automatically maintaining a constant temperature in the compressed gas inside the pipe, for all loads and all external temperatures, irrespective of whether the pipe-line is located underground or near or at the surface. This relates to the elimination of the need for embodying feautres, such as expansion joints, for taking care of expansion and contraction of the pipe. If, for providing greater accessibility, a location right at the surface is desirable, or on posts providing a height of a few feet above the surface, the greater variations in the surrounding temperature (as compared with a buried cable), no longer will constitute an obstacle.

There are other gases of higher dielectric strength than CO_2, which can be used at high compression, provided we maintain the temperature above the condensation point corresponding to that pressure. Notable examples are SO_2 and CCl_4. It is not known to the writer that much in the way of test results regarding the 60-cycle dielectric strengths of these gases at very high compressions, has been published. Figure 5 presents curves of the dielectric strengths, in crest volts per mil, corresponding to moderately uniform fields and a 500-mil spacing, for several gases for compressions up to some 60 ata. There is included the lower portion of an SO_2 curve. Throughout the small range of pressures for that curve (i.e., up to 20 ata), its dielectric strength is seen to be much greater than the dielectric strengths of air, CO_2 and nitrogen. When completely free from even the slightest trace of H_2O, the SO_2 gas exerts no deterioration on the materials which will be employed in the pipe-line transmission system or in the compressed-gas transformers which are a part of the system.

Comments on Carbon Tetrachloride.—CCl_4 gas is reported to have even better insulating characteristics than SO_2, and should be useful in cases where its higher vaporization temperature for a given compression, can be suitably taken into account in the arrangements for automatic control of the gas temperature. The dielectric properties of CCl_4 gas may be found to be so much superior as to permit of obtaining desired results in some cases, when a substantially lower compression is employed than would be needed with other gases. CCl_4 gas at a compression of 20 ata, probably will have a dielectric strength equal to that of CO_2 at 50 ata. It is well known that, even in its liquid form, carbon tetrachloride is an excellent insulation, although, in liquid form, it has proved insufficiently inert for some applications. As a compressed gas, however, it is quite probable that with appropriate design and choice of materials, it can be successfully employed in transformers, since there are now available, various insulating materials (such as flexible glass tapes and sheets, asbestos, mica, mycalex, and other inorganic materials), which reasonably can be expected to withstand any corrosive action of CCl_4 gas, even at quite a high temperature.

In a paper entitled: "D. C. Breakdown Strength of Air and Freon in a Uniform Field at High Pressures," pp. 132 to 135 of Vol. 60 (1941), of "A. I. E. E. Transactions," Trump, Safford and Cloud attribute the greater insulation strength of "certain compounds in the gaseous state, notably those which contain chlorine, fluorine or other negative atoms," primarily to two causes: (1) "the relatively large number of inelastic impacts which an electron may make in such gases with consequent loss of energy and ionizing power," and (2) "the electron affinity of the electro-negative particles in the gas, such as the chlorine and fluorine atoms." The authors state this to result in "the removal of free electrons from the gas with the accompanying formation of relatively inert negative ions."

At p. 511 of the March 15, 1937 (Vol. 51) issue of the "Physical Review," in an article entitled: "Effect of CCl_4 Vapor on the Dielectric Strength of Air," Rodine and Herb make the following observation:

"It may be of interest to note that . . . certain results indicated that CCl_4 vapor may be more efficient for suppression of corona discharge than for suppression of sparking."

The Impulse Strength of Compressed Gases.—In an earlier section of this article, allusion was made to an important advantage of the pipe-enclosed construction, namely, that it protects the high-voltage conductors from lightning. But if the pipe-enclosed part of the system is only employed as a branch or extension of an existing overhead line, this complete immunity from lightning surges, evidently is not provided. But even in those cases, there is the advantage that the amplitude of a lightning impulse entering the pipe-line, will be effectively attenuated as the impulse travels along the conductor, and, for usual conditions, it will become innocuous after traversing a very few thousand feet of the pipe-line. The rate and amount of the attenuation obviously depends upon the conditions of each case.

However, the general proposition of using compressed gas as insulation, continues to be criticized from the standpoint of those who still consider that compression may not increase the impulse strength of a gas to so great an extent as it increases the 60-cycle strength.

Only as recently as a very few years ago, it was quite widely believed by transformer specialists, and also by some underground-cable specialists, that: "increase in gas pressure has no effect on its impulse strength." Serious consideration of the use of compressed gases as insulation, was delayed several years by the persistence of this tradition. Gradually that claim has become greatly modified. It is now usually conceded that in fairly uniform fields (such as the gap between large-diameter spherical electrodes with not-too-great spacing), the impulse strength increases with increasing compression, and to the same extent as does the 60-cycle strength. Under those conditions, the impulse ratio of a gas is unity (the impulse ratio being defined as the ratio of the crest value of the voltage of a so-called 1½, 40 impulse wave, which can be withstood for three micro-seconds, to the crest value of the 60-cycle sinusoidal voltage which can be withstood for one minute). A 1½, 40 impulse wave is defined as a wave with a "front" so steep as to travel past a given reference mark in 1.5 micro-second and having a "tail" requiring 40 micro-seconds to decrease in amplitude to one-half of its crest value. With rod-gaps (which represent a fairly extreme case of a non-uniform field), the test results for the impulse breakdown voltage, sometimes are quite erratic, particularly for large spacings.

The obvious lesson is that all reasonable efforts should be made to provide for as uniform fields as practicable, either by using appropriate surface shapes in the designs, and smooth surfaces, or by so interposing barriers of solid insulating materials as to tend to decrease stress concentrations. Experience doubtless will teach us additional means for achieving the desired degree of field uniformity.

In an interesting and valuable paper by Mr. G. C. Nonken, entitled: "High-pressure Gas as a Dielectric," presented on Oct. 8, 1941, at an A. I. E. E. session, particular attention was given to impulse voltage phenomena with sphere-gaps and with rod-gaps, and for a wide range of spacings. The impulse employed was the standard 1½, 40 micro-second

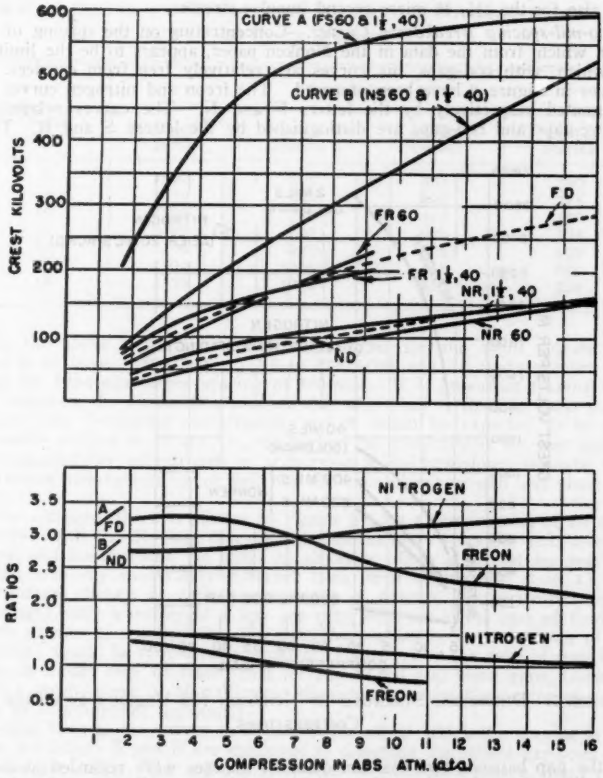


FIGURE 6.—CURVES FOR FREON AND NITROGEN (F & N) WITH SPHERE-GAPS AND ROD-GAPS (S & R) AND WITH 60-CYCLE AND IMPULSE STRESSES (60 & 1½, 40); THE SPACING BEING 800 MILS FOR ALL CASES.

wave. For rod-gap spacings greater than 800 mils, the results, in the writer's opinion, provide no satisfactory clues to the fundamental principles involved. For some compressions (when associated with spacings greater than 800 mils), the strength for a given rod-gap spacing, was greatest with 60-cycle stresses, while for other compressions but the same spacings, the breakdown

strength was greatest with impulse stresses. Both for impulse and 60-cycle stresses (in the case of rod-gaps with spacings greater than 800 mils), increased compression (for a given spacing), in some cases, increased, and in other cases, decreased, the breakdown voltage. Mr. Nonken's paper dealt with two gases, nitrogen and freon. In the rod-gap tests, these two gases behaved very differently from one another, not only for the 60-cycle stresses, but also for the 1½, 40 micro-second impulse stresses.

800-mil-spacing Breakdown Curves.—Concentrating on the spacing of 800 mils, which, from the data in the Nonken paper, appears to be the limit up to which, with rod-gaps, his curves are relatively free from caprices, the curves in Figure 6 have been prepared. The freon and nitrogen curves are designated respectively by the letters F and N. The curves relating to sphere-gaps and rod-gaps are distinguished by the letters S and R. Tests

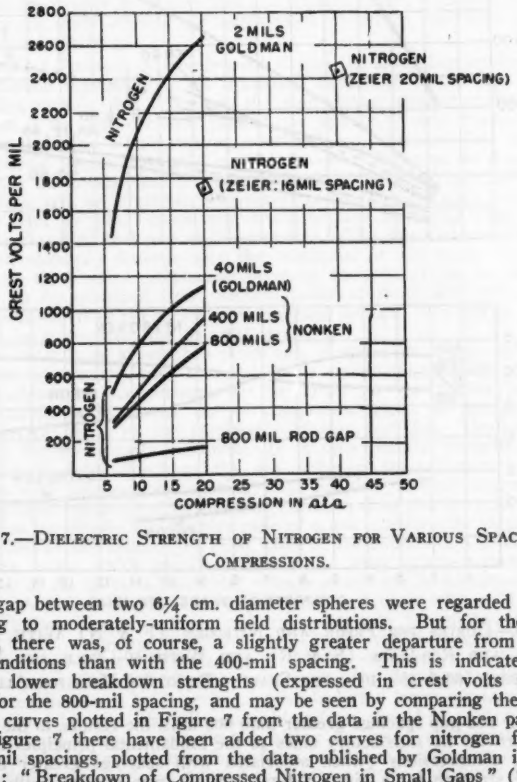


FIGURE 7.—DIELECTRIC STRENGTH OF NITROGEN FOR VARIOUS SPACINGS AND COMPRESSIONS.

in the gap between two 6¼ cm. diameter spheres were regarded as corresponding to moderately-uniform field distributions. But for the 800-mil spacing, there was, of course, a slightly greater departure from uniform-field conditions than with the 400-mil spacing. This is indicated by the slightly lower breakdown strengths (expressed in crest volts per mil), found for the 800-mil spacing, and may be seen by comparing the 800- and 400-mil curves plotted in Figure 7 from the data in the Nonken paper.

In Figure 7 there have been added two curves for nitrogen for 40-mil and 2-mil spacings, plotted from the data published by Goldman in a paper entitled: "Breakdown of Compressed Nitrogen in Small Gaps" ("Comptes Rendus, Doklady, de l'Academie des Sciences de l'U.R.S.S.," 1938, Vol.

XVIII, No. 2). The results of two tests by Zeier are also plotted in Figure 7. From Goldman's 2-mil and 40-mil curves, and Nonken's 400- and 800-mil curves, the following table has been prepared. For nitrogen at various compressions up to 18 ata, the table shows the measured 50- and 60-cycle breakdown strengths in crest volts per mil:

TABLE OF BREAKDOWN STRENGTHS OF COMPRESSED NITROGEN FOR 50- AND 60-CYCLE STRESSES.

Compression in ata.	Crest, Volts per Mil.			
	2-mil Spacing.	40-mil Spacing.	400-mil Spacing.	800-mil Spacing.
6	1500	500	337	300
8	1870	640	425	375
10	2100	770	525	450
12	2280	860	620	525
14	2400	950	705	590
16	2500	1000	790	655
18	2570	1050	880	720

In the above table, the dielectric strengths for the 2-mil spacing are seen to be from (1500/300 =) 5.0 to (2570/720 =) 3.6 times greater than with the 400-times-larger spacing of 800-mils. It is important to note that, for nitrogen, the above data indicate that the trend is for this ratio to decrease with increasing compression, and it might be expected to be considerably smaller at 50 ata, i.e., the higher the compression, the less may be the susceptibility of nitrogen to a decrease in its breakdown strength with increasing non-uniformity of field for the case of sphere-gap and plane-gap tests.

For nitrogen, there is plotted in Figure 8 (for a compression of 20 ata), a curve with the 50- and 60-cycle stresses, in crest volts per mil, as ordinates, and the spacings (in mils) as abscissæ. It is seen that for spacings which are only moderately different from each other (say 2 to 1), the percentage change in dielectric strength is (except for extremely small spacings), only a matter of a few per cent, whereas in the case of fields of much greater non-uniformity, the percentage change (as a function of the spacing) would be considerably greater. [NOTE: For the sake of completeness, it should here be stated that for the 40-mil and 2-mil gaps, Goldman used a steel sphere of 20-millimeter diameter, opposite the center of a flat disc of 50-millimeter diameter.]

Going back to the curves in Figure 6, for all of which the spacing is 800 mils, the letters S and R are employed to designate the sphere-gap tests and the rod-gap tests. The rod-gap electrodes were ½-inch square, brass rods. This construction of gap is regarded as typical of a decidedly non-uniform field.

60-cycle breakdown tests were made both with the sphere-gap (S) and with the rod-gap (R), as also 3 microsecond breakdown tests with a 1½, 40 impulse wave. The 60-cycle tests are designated by 60, and the impulse tests by 1½, 40. For the sphere-gap, the breakdown voltage, for all compressions, is the same with 60 cycles as with the standard 1½, 40 impulse wave; i.e., the impulse ratio is unity.

As an illustration of the plan of designation employed in the Figure 6 curves, the one marked "NS 60 & 1½, 40," shows for nitrogen (N) and

for compressions up to 16 ata, the sphere-gap breakdown voltages for 60 cycles (60) and also for the 1½, 40 impulse wave (& 1½, 40). The tests for that curve were made with the sphere-gap (S), and the spacing was 800 mils.

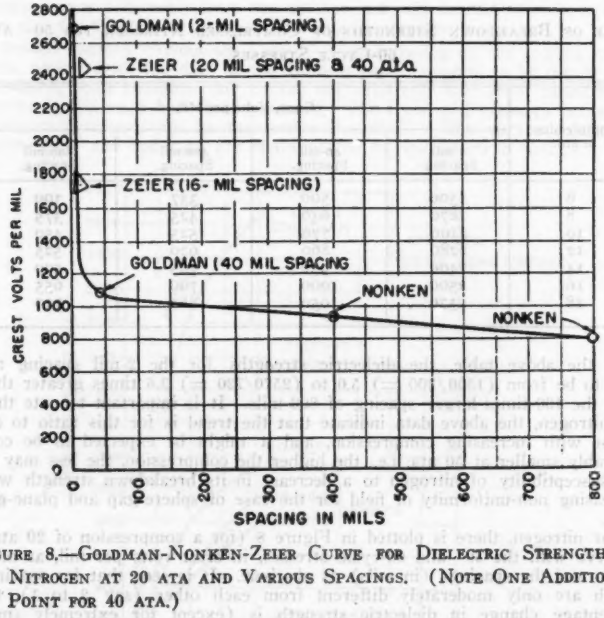


FIGURE 8.—GOLDMAN-NONKEN-ZEIER CURVE FOR DIELECTRIC STRENGTH OF NITROGEN AT 20 ATA AND VARIOUS SPACINGS. (NOTE ONE ADDITIONAL POINT FOR 40 ATA.)

But for the rod-gap (for the spacing of 800 mils used for all the curves in Figure 6), the two kinds of stress (60 cycle and impulse) result in different values of the breakdown voltage. The differences are, however, so relatively small that there have been drawn two dotted lines, FD ("freon dotted") and ND ("nitrogen dotted"), which can be considered as roughly representative of the rod-gap breakdown voltages for freon and nitrogen respectively, irrespective of whether the stresses were 60-cycle or impulse.

The impulse ratios for nitrogen and freon for rod-gaps are shown in the two lowest curves in Figure 6. The impulse ratio for the sphere-gap, for gases at all compressions, is unity, provided that the diameters are sufficiently large relatively to the spacing.

The curves A/FD for freon, and B/ND for nitrogen, probably are innovations. It is believed that they provide an important criterion of the suitability of the gases as dielectrics at high compressions and high voltages, even when the available facilities do not permit of obtaining direct tests at more than rather low compressions and relatively low voltages. Thus if we examine the A/FD curve, we shall see that for freon, the dielectric strength in a rather non-uniform field, increases from about three-tenths of the sphere-gap strength at the low pressure of only 2 ata, up to five-tenths

when the pressure is increased to 16 ata, and that the shape of the curve indicates a continuance of the increase with further increase in the compression. This result for freon agrees with the trend observed for nitrogen in the sphere-gap and "sphere-plane" tests on which is based the table on p. 161.

The opposite trend is seen to be indicated with the B/ND curve representing nitrogen, the ratios of rod-gap to sphere-gap strengths being respectively 0.33 and 0.29 for compressions of 2 ata and 16 ata. The curves thus indicate nitrogen to be much more unfavorably affected by increased non-uniformity of the field than is freon, and the shape of the B/ND curve indicates that the inferiority of nitrogen in this respect will be even more pronounced at compressions higher than those shown in Figure 6. This increasing inferiority of nitrogen in non-uniform fields as the degree of compression is increased, is precisely the opposite to the trend deduced from the values in the table on p. 161 which related to sphere-gap and sphere-plane tests. The inconsistency should be investigated by means of further tests.

Although their methods of approach were quite different. Zeier and Finkelmann previously have reported adversely as to the merits of nitrogen in the matter of its suitability as an insulator when highly compressed. Provided the trend observed for freon of better retaining its dielectric strength in non-uniform fields the higher the compression, is confirmed by further investigations, then the outlook would appear especially favorable also for SO_2 and CCl_4, because of the fact that they share in some respects the physical and chemical properties of freon.

At p. 208 of the 2nd edition of Arnold Roth's fine treatise entitled "Hochspannungstechnik" (Springer. Vienna, 1938), Roth states:

"The impulse ratio is very dependent upon the electrode shape. It is high with points and low with plates and spheres. The sphere gap can therefore be used for measuring the crest value of impulse waves, provided its spacing is not chosen too great with respect to the sphere diameter."

In addition to the effect on the impulse ratio of the physical design of the gap, we now learn from the two lowest curves in Figure 6 that the impulse ratio for an 800-mil spacing, varies considerably with the degree of compression, and also is different with different gases.

Compressed Gas for Power Transformers.—In some quarters, it has been felt that the need for employing higher-than-usual temperatures in order that CO_2, SO_2, and CCl_4 shall not condense at the degree of compression needed for high insulation strength, is a requirement which generally will disqualify them from use at high pressures for insulating and circulating purposes. The writer disagrees with this conclusion, and believes that on the contrary the requirement to provide the corresponding high temperature often may be associated with advantages of importance.

Thus, in the case of a compressed-gas transformer, the stream of ascending gas will be heated by the losses as it passes over the winding surfaces and ducts. Condensing conditions will be provided in an appropriate portion of the transformer tank, or in a special compartment into which the hot gas will pass on its arrival at the top of the transformer tank. Then the dielectric will descend by gravity in its completely or partly condensed condition, and will be again heated and vaporized in the middle or lower portions of the tank where the active material of the transformer is located. Obviously, a fan or blower may be employed to circulate the dielectric at higher speeds in the interests of the desired thermal design, and possibly also to increase the dielectric strength by increasing the mobility of the gas for the degree of compression employed.

The MacLaren Effect.—Long ago it was pointed out by MacLaren (Vols. XXX and XXXI, 1911 and 1912, of the "A. I. E. E. Transactions"), that if a transformer core composed of laminations prepared with suitable physical treatment, and of suitable chemical composition, is operated at an appropriately-high temperature, its hysteresis loss will be greatly reduced.

In recent discussions of this subject, transformer specialists have asserted that the decrease in hysteresis loss due to the MacLaren effect, will, at the flux density employed, be accompanied by such a decrease in permeability, and corresponding increase in the required magnetizing component of the transformer current, as to cancel any advantages as regards decreased core loss in the transformer. This, however, does not prove to be the case if the appropriate kind of core material is used. Tests to decide this point were specially made on one of the very best brands of low-loss transformer iron. These tests showed that the increases in the magnetizing current at the desired high temperature were of only such moderate amount as not to be of any consequence with respect to the very advantageous use of the MacLaren effect in transformer design. Since, however, transformer oil of reasonable cost gradually deteriorates by sludging unless the temperature is kept down to a very moderate value, and since, until recently, appropriate insulating materials which withstand high temperatures for long periods, had not been developed in forms in which they could be used effectively in transformers, the MacLaren effect could not be used to any advantage in oil-type power transformers. With the increase in our knowledge of how to use compressed gas successfully as insulation and as a circulating medium, together with the present availability of turn and layer insulations of flexible-glass-tapes and sheets, spacers and supports and barriers of porcelain, glass, asbestos, mica, micalex and other heat-resisting materials, there ceases to be any good reason for not resorting to the high-temperature operation of transformers when sufficient advantages will accrue therefrom. There will also be the usual great gains accompanying the decreased size and weight and cost associated with the proper employment of high temperature in the design of electrical machinery. With appropriate designing, the efficiency will not be impaired by the fact of the use of high temperature.

"Thermal-screen" Transformers.—One arrangement for the employment, in transformer construction, of these thermal principles in combination with compressed-gas circulation, consists in interposing a "thermal screen" between the core and the windings. A considerable portion of the heat from the core will escape by flowing outward across the thickness (say 3/8 inch or so), of the thermal barrier, and thence will be carried away mixed with the lower-temperature heat from the windings.

Due to the use of the thermal barrier, the windings may be operated at a very much lower temperature than that maintained in the core. Nevertheless the winding temperature-rise (by resistance) may, in appropriate cases, amount to 140 degrees C., or even more. With a typical ambient temperature of 30 degrees C., this corresponds to a winding temperature (by resistance) of 170 degrees C. or over.

The greater part of the gas stream will pass up through the windings outside of the thermal barrier, and will rise in temperature up toward, say, some 30 degrees C. less than the temperature of the windings, as determined from resistance measurements.

Making Practical Use of Vaporization and Condensation of the Circulating Gas.—Freed from the temperature limitations imposed by oil immersion, several desirable but heretofore inapplicable features can be embodied in power transformers. Some of these relate to the utilization of vaporization and condensation. In other words, we may employ our dielectric for a part of the time in the gaseous, and part of the time in the liquid, form. It

will be seen from the SO_2 curve in Figure 9 that in order that SO_2 shall retain the gaseous form at a compression of 50 ata, its temperature must exceed 130 degrees C. A margin of some 10 degrees C. probably is desirable in order to avoid the liability of having any liquid mist held in suspension in the gas stream. Thus its temperature should be increased to about 140 degrees C.

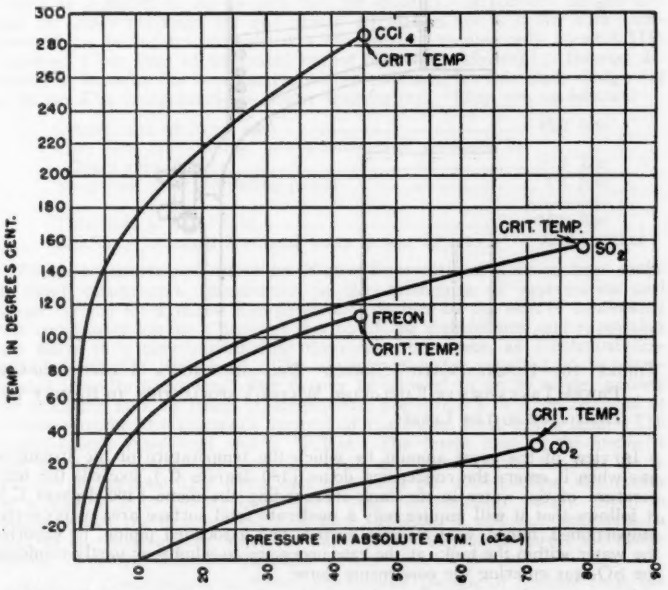


FIGURE 9.—TEMPERATURE-PRESSURE VAPORIZATION CURVES OF FOUR GASES.

From Figure 5 it is seen that SO_2 gas, at a compression of 50 ata, has a much higher dielectric strength than air or CO_2 at that compression.

We may so design the circulation, that part of the gas stream shall pass over the windings outside of the thermal barrier, at a mean temperature of some 140 degrees C. On emerging into the spaces above the windings, it will be joined by, and will mix with, a stream of SO_2 gas which has attained a far higher temperature in traversing passages adjacent to the hot core, but a portion of which has had its temperature greatly reduced in escaping across the thermal barrier (with a thickness of a quarter of an inch or more) into passages between the outside of the barrier and the inside surfaces of the winding. Let us assume that the average temperature of the stream of gas after traversing the barrier is well above 200 degrees C., and that the mixture formed by the joining of the two streams has an average temperature of, say, 180 degrees C., and that the resultant stream enters the condensing dome, indicated diagrammatically at D in Figure 10, at that temperature.

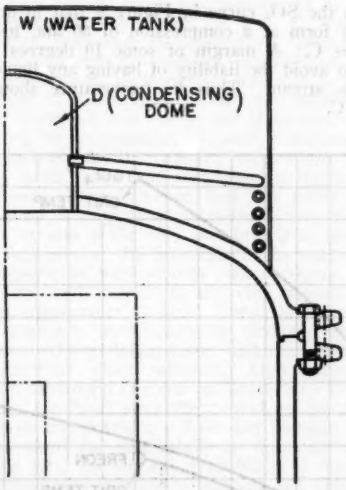


FIGURE 10.—DIAGRAMMATIC SKETCH RELATING TO A COMPRESSED-GAS POWER TRANSFORMER EMPLOYING WATER-VAPORIZATION TO REMOVE THE HEAT DUE TO THE LOSSES.

In view of the great amount by which the temperature of the stream of gas when it enters the condensing dome (180 degrees C.), exceeds the temperature of the water in the tank surrounding the dome (100 degrees C.), it follows that it will require only a moderate total surface area of properly-proportioned, finned, heat-transfer surface and associated piping, to vaporize the water within the tank, at the rate necessary to wholly or partly condense the SO_2 gas entering the condensing dome.

Evacuator.—It may be desired to further decrease the temperature of the boiling water in the tank (W, in Figure 10), so as to have a greater difference of temperature between the compressed gas in the dome (D), and the water in the tank (W). The greater this difference in temperature, the smaller need be the total heat-transfer surface which will be required. For accomplishing this purpose, we may employ a blower designed for the high speed and high operating temperature used successfully in super-chargers. This evacuator will throw or suck out through suitably shaped and located apertures, the steam above the water surface, at such a volumetric rate as to reduce the pressure on the water surface, and will consequently also reduce the vaporization temperature. The power consumed by this auxiliary will slightly decrease the total efficiency of the transformer installation, but the simplicity of the method sometimes will make it preferable to resorting to a condenser, when a vaporization temperature lower than 100 degrees C. (say 90 degrees C), is desired.

The cooled dielectric will descend by gravity through suitable passages leading to the lower portion of the transformer tank. It will enter this lower portion at a temperature of (for example) 125 degrees C. The dielectric next may pass over hot-copper base-plates, which are in intimate

thermally-conducting relation with the bottom part of the very hot transformer core, from which a stream of heat flows to, and is absorbed by, the dielectric. As the result of this heat transfer, the dielectric is vaporized, and raised to a temperature suitably in excess of 130 degrees C., ready for the next cycle of heat-transfer events.

Power Required for Compressed-gas Circulation.—It requires almost negligible power to circulate the stream of compressed gas at very high speeds (such as a matter of 500 to 1000 feet per minute). In certain designs laid out for study purposes, the gas-stream circulation for a 12,500 Kva compressed-gas power transformer, was estimated to require only about 5 HP. (0.04 of 1 per cent of the rated output of the transformer). Interest attaches to knowing the losses and efficiency estimated for this study-design for a 12,500 Kva compressed-gas power transformer. They are as follows:

Copper loss at rated load	46.0 Kw
Core loss (not taking into account any decrease by MacLaren Effect)	21.5 Kw
Stray loss plus ventilating power	7.5 Kw
Total loss at rated load	75.0 Kw
Efficiency at rated load and unity power factor:	99.4 per cent

Power-transformer Cooling by Water Vaporisation.—Let us now make a rough quantitative examination of the economics of vaporization and water cooling for a 12,500 Kva power transformer by the plan of condensing the compressed gas in a dome at the top of the transformer, and vaporizing the water in a tank surrounding the condensing dome, as illustrated diagrammatically in Figure 10. The amount of water required to be evaporated annually is so small that it may be allowed to go to waste, passing off from the tank as steam at atmospheric pressure. It will be replaced at a rate governed by automatic control of the water level in the tank. The transformer's rated load loss is 75 Kw. The latent heat of the steam is 286 w. hour per pound. and the make-up water comes to 760 U. S. gallons per 24-hour day. At a cost of 7 cents per 1000 gallons, this comes to a total cost of twenty dollars per year for make-up water. Even in places where the cost of water is much greater, it will not amount to a sum of any consequence, since the value of the annual output of the transformer is several hundred thousand dollars.

Probable Consequences to Power-transformer Design, of Release from the Limitations Imposed by the Use of Oil.—It is evident that the preliminary suggestions which have been given in this article, concerning new procedures in power-transformer design, which will become practicable with the release from the limitations associated with the use of oil, simply are indicative, and doubtless not in all respects nor in every instance, the best for accomplishing the desired objects. Very many alternatives will be devised to take advantage of these groups of new factors, and many minds will work independently in devising "better ways."

There is little or no originality in these vaporization-cooling methods. However, their effectiveness for use in transformers is greatly increased when oil's low temperature limit is removed. Vaporization-cooling principles may be worked out in many different ways, but a very serious impediment to their use in transformers was the low service temperature necessary when oil was employed for circulation and insulation.

Locating the Transformer Underground.—The elimination of (1) high-voltage bushings (often having heights of over 15 feet above the top of the transformer tank), and (2) the absence of the fire risk associated with the use of transformer oil of usual cost, combine to permit compressed-gas

power transformers to be installed inside of substation buildings. An underground location also becomes attractive. Aside from the short, low-voltage bushings, nothing need emerge from the transformer tank except a steel pipe of a few inches diameter. This steel pipe contains compressed gas and extends from the transformer tank to the transmission pipe-line. The latter should, at any rate for the portion at or within the sub-station building, be located a few feet above the floor level.

A typical transformer substation will contain 8 transformers (4 step-down and four step-up, 2 of the 8 being spares), or multiples of these numbers. All switch-gear, such as dis-connectors and the low-voltage circuit-breakers, will be installed in metal enclosures. For structural reasons, the transformer's tank should be of rather small diameter and great total height, often 12 to 20 feet or more. Of this total height, all but a few feet should be sunk in a vertical, cylindrical pit, below the floor level. The few feet of the tank which project above the floor level will have a much thicker steel wall than the 12 to 20 feet occupying the cylindrical pit. The protruding upper end provides for convenience of installing and for subsequent accessibility. The tank is to be regarded as a permanent compartment. The design will permit of the removal, servicing, or replacement of the actual transformer.

A tank installed in this way may be made of thinner metal than otherwise would be required, since it will derive from the opposing pressure of the surrounding pit wall great mechanical support to resist the internal gas pressure. The space between the internal wall of the pit and the external surface of the tank will be filled with a strong mass of suitable material to supplement the strength of the steel wall of the tank. This filling material will be of such composition and will be so applied as to exert a great and evenly-distributed compression on the entire outer surface of the tank.

In a compressed gas, 60-cycle, 165,000 volt, 12,500 Kva transformer, this underground location, with the thinner tank wall, reduces by some 5 tons the amount of steel required for the tank wall. As compared with an oil-type transformer for the same rating, there is eliminated the need for several thousand gallons of transformer oil. Another large item of economy as compared with the oil equivalent is effected by eliminating the expensive, and in other respects undesirable, high-voltage entrance bushing. It is evident that these savings, together with the considerable savings effected by being able to operate the transformer at temperatures which could not be permitted with the oil type, certainly will greatly decrease the compressed-gas transformer's cost much below the cost of an oil transformer for the same rated output and voltage.

Further Consideration of Particular Features of the Pipe-enclosed, Compressed-gas, 60-Cycle, Transmission System.—Our attention must now again be turned back to the transmission line. Although the step-down and step-up compressed-gas transformers are constituent parts of the transmission system, there is no need for employing the same gas or the same degree of compression in the one as in the other. Stop-joints will serve to separate them, and will also permit of sub-dividing the long-distance transmission line into any suitable number of short sections. The subject of effective stop-joints for a compressed-gas system such as we are considering has been carefully studied, but it will not be taken up in this already very long article, further than to state that the associated technical problems are much simpler than the corresponding technical problems encountered with solid-insulated, high-voltage underground cables.

In this transmission-line project, there usually will not be employed the same voltage throughout the entire length. The economics of each particular case will indicate very high voltages to be appropriate in traversing some districts (where, for example, infrequent outlets are required), and

quite low voltages in other districts. Two such differing-voltage sections are in electrical communication with each other only through groups of step-down and step-up compressed-gas power-transformers whose low-voltage secondaries are inter-connected through low-voltage circuit-breakers. By opening the circuit-breakers, the two sections are completely separated. The interposition of these transformer groups permits of employing circuit-breakers of much lower cost and greater dependability than are available for the currents and high voltages contemplated for (1) transmission systems, (2) interconnections, and (3) power pools, for great amounts of power.

Barrier Effect.—The insulating and supporting design shown in Figure 2 has the further advantage that the presence of the solid insulating barrier D will serve considerably to increase the breakdown strength of the composite structure. Such barriers, properly located, serve to decrease stress concentrations in non-uniform fields, and it may reasonably be expected that the structure will have a considerably greater breakdown strength than without such an interposed barrier. The subject is, however, complicated, and there is but little experimental data for guidance. For systems employing still higher voltages, two or more properly-spaced, concentric barriers should be very effective.

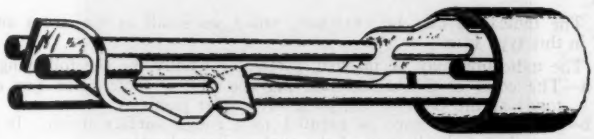


FIGURE 11.—DIAGRAMMATIC SKETCH OF (1) ENCLOSING PIPE, (2) SPACING INSULATOR, AND (3) 3 HIGH-VOLTAGE 60-CYCLE TRANSMISSION CONDUCTORS FOR UNDERGROUND SYSTEM FOR TRANSMISSION OF LARGE AMOUNTS OF POWER TO GREAT DISTANCES.

If all three conductors are located in a single pipe, then the resultant of the currents in the three conductors is zero, and the loss in the material of the pipe will be of small amount. Figure 11 illustrates diagrammatically a model with three conductors in a single pipe. Interest attaches to the cranked type of insulating support there shown.

MISCELLANEA OF INTEREST TO NAVAL ENGINEERS.

FLUORESCENT MAGNETIC INSPECTION.—A new magnetic particle test, called "Magnalo", based on the use of fluorescence, is described by W. E. Thomas of the Magnaflux Corporation. This test method reduces the possibility of misinterpretation and eliminates trouble sometimes occasioned by poor color contrast and inaccessibility of some areas when conducting the usual magnetic particle inspection. This article is copied from the November, 1942, issue of Metals and Alloys. Another article on fluorescent crack detection, describing the "Glo-Crack" process of Colloidal Research Laboratories, London, will be found in Engineering, September 4, 1942.

Practically all inspection methods depend on visual examination by the inspector. The use of rules, dial gauges, micrometers and other measuring devices require the reading of a scale; surface finish testing requires the reading of a Profilometer or similar instrument, or merely visual examination; magnetic analysis inspection relies on the reading of a voltmeter; X-ray and gamma ray radiography depend on the interpretation of lights and shadows of the film. In a similar way the magnetic particle method as accomplished with Magnaflux dry powders and pastes for the wet method requires that the inspector search for those accumulations of the particles that form the indications of important discontinuities.

Magnetic Particle Inspection.

Of the inspection methods mentioned above, the one requiring the most care, from the purely "visual examination" standpoint, is magnetic particle inspection. There are a number of contributing factors which may be considered:

1. The inspector does not know where the indication may be. He must carefully scan the entire surface of the part as he turns it in his hands. He must not pass over any indication either through carelessness, because of fatigue, or because he believes that he has previously examined a certain area.

2. The indication may be extremely small, as small as the cross on the "t" in this type face.

3. The indication may be masked, partly, or wholly, by the following:
   a—The color of the background may be of the same color (or color tone) as the color of the paste or powder particles.
   b—The indication may be parallel to a rough surface finish. It may even lie at the bottom of the surface irregularities.
   c—The indication may extend, partly or wholly, into holes, borings, or deeply machined grooves.
   d—The indication may be masked because it occurs along a line at which a so-called "false indication" may be expected or, in fact, exist.
   e—The indication may be of the wide, fuzzy type, indicative of a subsurface discontinuity, and may be difficult to interpret because of the lack of a sharply defined line built up by the particles.

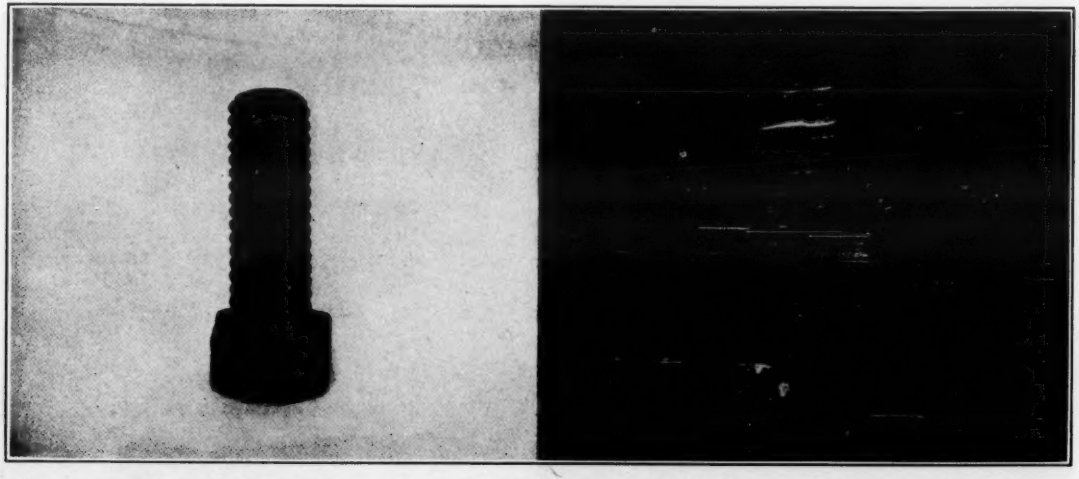
4. Parts inspected by the wet method are covered with the light distillate oil used as a suspension medium for the paste particles. This oil film causes disturbing high lights. Highly finished parts inspected by either the wet or dry methods also cause high lights which interfere with the inspectors visions.

Because of these factors, and because of the widely increased use of the method, the engineers who have developed the methods and equipment used, maintained a constant program of research pointing to the development of dry powders, and paste materials for the wet method, which would afford maximum sensitivity, heavy build-up of indications, and visibility.

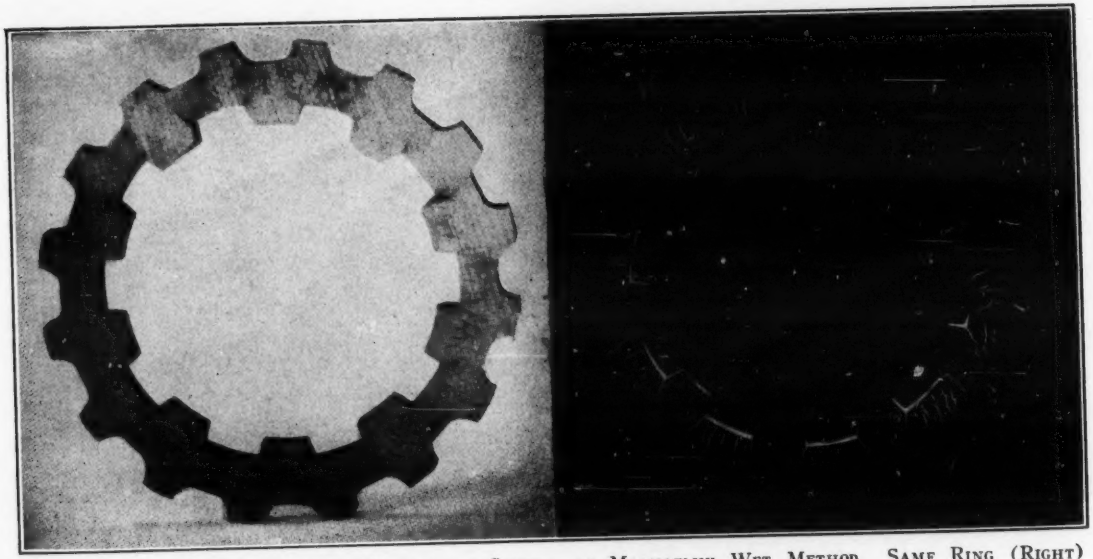
The original material was the widely used gray powder. Later developments were the black and the red powder. These colors have given industry a wide enough range to solve, in a fairly satisfactory manner, the problem of color contrast. Pastes for the wet method were developed in black and in red. There remains the problem of formulating a light colored wet paste material.

Fluorescence.

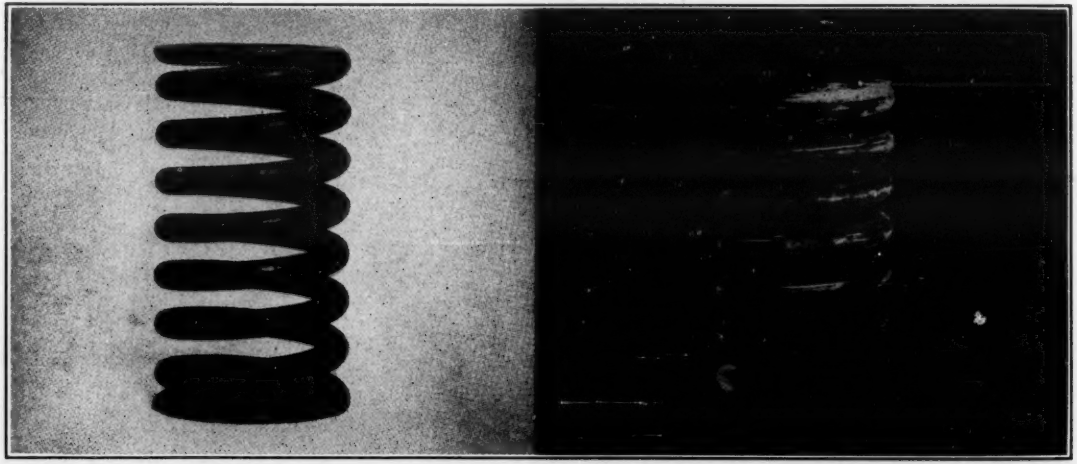
Several years ago it first seemed possible that fluorescent (or phosphorescent) indicating particles would be ideal from the standpoint of



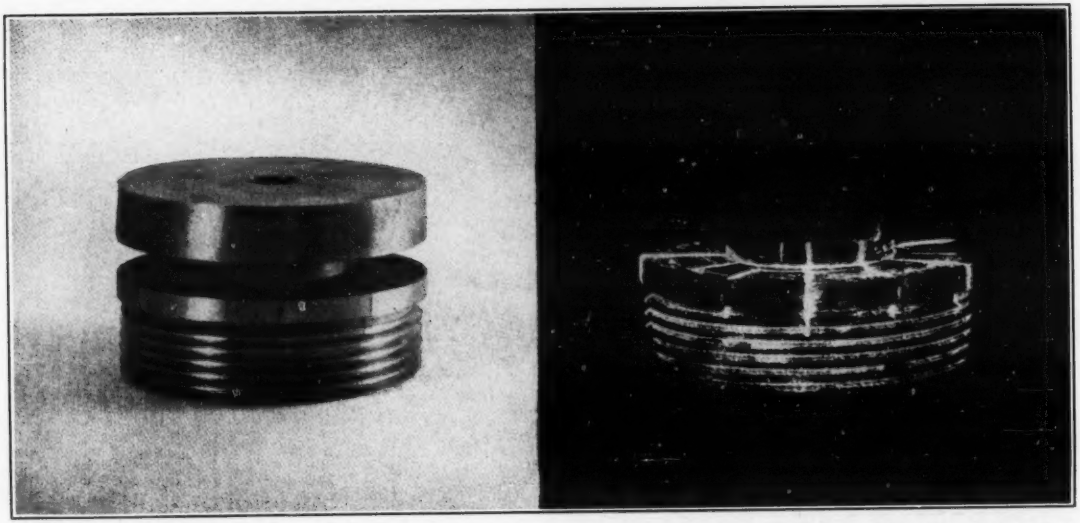
(Left) Bolt With Transverse Crack in Fourth Thread From End as Shown by Magnaflux Wet Method. Same Bolt (Right) With Crack Shown by Magnaglo Wet Method.



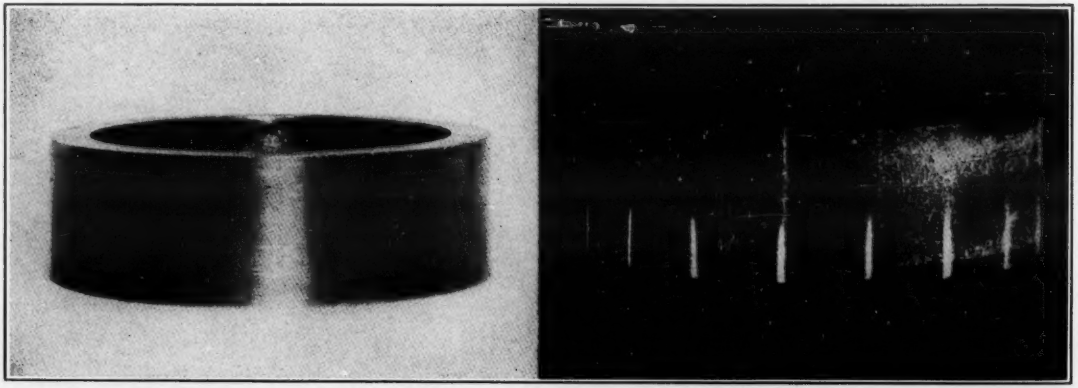
Splined Spacer Ring (Left) With Indications Shown by Magnaflux Wet Method. Same Ring (Right) With Indications Shown by Magnaglo Wet Method.



(Left) Valve Spring Showing Seams as Indicated by Magnaflux Wet Method. Same Spring (Right) Showing Indications by Magnaglo Wet Method.



A 37-Millimeter Breech Part (Left) Showing Cracks Indicated by Magnaflux Wet Method. Same part (Right) With Indications Shown by Magnaglo Wet Method.



A 4-Inch Diameter Ring (Left) Containing Small Holes Drilled Into the Ring From the Lower Face. The Holes Are the Same Size and Are Located Progressively Farther From the Outside Diameter From Left to Right in the Photograph. The Indications Are Those of Magnaflux. Same Part (Right) Showing Indications as Developed by Magnaglo Wet Method. (Above the Fourth Indication From the Left, There Is An Apparent Continuation of the Indication Which Is Not Shown by Magnaflux. This Is Apparently the Result of a High Light and Is Not a True Indication. The Negative Was Not Re-touched in Any Way, and the Photograph Gives An Apparently Incorrect Indication.)

eliminating most of the problems of the masked or partially masked, indications. Different fluorescent or phosphorescent materials were tried as coating on the powder and paste particles, but always one or more adverse factors caused their rejection. One of the main difficulties was the fact that so many of the commonly known compounds with these properties tend to produce cancer, and hence are not suitable for general use. Results were encouraging, however, and the work was carried on slowly. The joining of the knowledge of chemists with considerable background in "fluorescence" and of physicists working with the magnetic particle method resulted in a suitable material for the wet method recently announced under the trade name "Magnaglo." A dry powder is now in the development stage.

There are many whose knowledge of fluorescence and "black" light is limited, and the following paragraphs will serve to give a working knowledge of these terms.

Fluorescence is a term used to describe the effects produced by certain chemical products that exhibit the peculiar property of emitting visible light from within themselves during activation by "near ultra violet" or black light. These materials absorb the invisible energy, alter its wave length and emit the energy in the form of light which the eye can see.

"Black" light is the term popularly applied to the invisible radiant energy in that portion of the ultra-violet spectrum just beyond the blue of the visible spectrum. The visible spectrum ranges roughly between 4000 and 8000 Angstrom units in wave length. The black light range is between 3000 and 4000 Angstrom units in wave length. This black light is not to be confused with the ranges of ultra-violet used for therapeutic, sterilization, germicidal and health purposes, which are below 3000 A.U. and which are potentially harmful to the eye in varying degree.

Near-ultra-violet radiations are present in the emission from the sun, the carbon arc, the mercury vapor arc, the iron spark and other sources. It is usually accompanied by some visible light and some infra red (heat). The most potent and practical source is the high-intensity mercury arc, a discharge between two electrodes in an atmosphere of inert gases and mercury vapor. The visible radiations produced are substantially eliminated in black light equipment through the use of an auxiliary filter glass, highly colored to absorb approximately 97 per cent of the visible radiations while passing a maximum of the desired invisible radiations.

Practical Procedure.

In making up a wet bath for the magnetic particle method, the suspension commonly used is 1 to 1.5 per cent solid particles in the light oil medium. The amount of paste is as large as possible, but small enough to avoid an objectionable overall coating of the part by the paste. Even this 1 or 1.5 per cent suspension leaves a certain amount of particles all over the part, but their extremely small size makes the film practically invisible.

The fluorescent magnetic particles are, however, much more visible under black light than Magnaflux paste particles of the same size under visible light. Therefore, the same 1 to 1.5 per cent suspension of fluorescent paste leaves a very visible, and disconcerting fluorescent film over the part being inspected. It is necessary to reduce the percentage in suspension drastically to eliminate this film. The percentage actually used ranges from 0.2 to 0.3 per cent by volume of paste to volume of oil. This percentage is checked by allowing 100 c.c. of the suspension to stand in a centrifuge type of graduate. After 30 minutes, the cubic centimeter reading of the solid paste which has settled out of suspension is read.

When this small amount of paste is used the indications, while readily visible under black light, are not easily seen under visible light, because the volume of the build-up of the paste particles is very small. If this is objectionable to the inspector, a mixture of the non-fluorescent red paste and the fluorescent material may be used. If this is done, the suspension may be checked by the same settling test that is used to determine the number of cubic centimeters of the mixture of the two pastes, but it will not determine whether a sufficient volume of the fluorescent material is present. This is accomplished easily by keeping a defective part with a very small indication as a test piece, and making a test with this piece at intervals to determine whether the indication shows up readily with sufficient fluorescence.

Comparison of Methods.

As stated before, the purpose of the fluorescent method is to improve the visual inspection operation. Referring back to the factors affecting this operation, when using standard red or black "visible" pastes, we see that they are the following:

1. The necessity of carefully scanning the entire surface.
2. The small size of some indications.
3. Masking or partial masking of the indications by:
   a—Color of background.
   b—Irregular surface finish.
   c—Holes or borings.
   d—False indications.
   e—Relatively small volume of particles over subsurface indications.
4. Strong headlights.

These factors are considerably changed when using the fluorescent paste as outlined below:

1. If the test piece is examined in darkness, any small light source, such as a fluorescent indication attracts and draws the eye immediately. The size and complexity of the part do not, therefore, offer merely the opportunity to miss the indication as in visible light.

2. The extreme fluorescence of the indications make the visibility, under black light, so high that even very small indications catch the eye.

3. Masking of the indication is eliminated.
   a—Visibility depends upon reflective values. These values may be accurately measured. For example, the reflective value of this white paper is, perhaps 80 per cent. The reflective value of this black ink is, perhaps 4 per cent. Therefore the color contrast of a good white and a good black is approximately 20 to 1. Actually, in magnetic particle inspection, the contrast between the background and the indication may be only a small fraction of this ratio. If we are in absolute darkness, then even a very, very small light source gives a contrast of infinity. Actually we do not usually inspect in absolute darkness, but with sufficient visible light so that the outline of the part is visible. Even so, the contrast between the very dark surface and the glowing indication is much greater than the usual ratios when using the usual black or red pastes available.
   b—For the same reasons given above. surface finish does not disturb the inspector as he looks only for a brilliant line or indication, and not for a contrast between the indication and the surface of the part.
   c—As the indication forms its own visible light rays, the inspection of holes or borings can be much easier as it is frequently difficult to

project a visible light into the hole and yet have the eye in a favorable position to view the indication.

d—False indications, particularly those caused by leakage fields at sharp corners and changes of section are much reduced by the use of the fluorescent method. The greatly reduced volume of paste particles in suspension is not conducive to heavy build-up in weak fields. The reduced volume of particles also results in a cleaner washing off of the surface of the part. Thus, the fluorescent method allows the inspection of threaded parts, and of corners where such areas have been quite difficult to examine with Magnaflux pastes unless the indication was large.

e—Sub-surface discontinuities cause weaker external leakage magnetic fields than surface defects because of the much greater permeability of the iron or steel over the discontinuity. These leakage fields extend over a much larger area than those caused by a surface crack or seam. For these reasons the extremely small ferromagnetic particles in paste form do not build up well into sharp clearly defined heavy indications. Many indications are actually formed with these pastes that are not located by the inspector purely because they appear the same as many other areas of the surface of the test piece which have a light visible accumulation of particles. The fluorescent particle indications on the other hand can be seen under black light when the same non-fluorescent particle indication is not noticeable in visible light.

4. The question of visible light highlights does not, of course, seriously enter into the inspection under black light. The highlights, or reflections from the part are all of the near ultra violet, or invisible range.

The accompanying photographs illustrate some of the most important differences between visible red paste and fluorescent paste indications. Those taken of the red paste indications were taken under visible light and in all cases were lighted so that the indication would appear as distinctly as possible. Those taken of the fluorescent indications were taken under ultra violet light.

In conclusion—the fluorescent method appears to be capable of speeding up the most time-consuming part of this magnetic particle inspection method, that of visual examination; avoiding many of the troubles due to false indications and highlights, and eliminating difficulties of color contrast and inspection in hard-to-see areas. The material was disclosed, early in its development, to the Army Air Force and Navy Bureau of Aeronautics, and they have followed its development with interest.

This material should not be confused with the new "black light" inspection method also recently announced by the Magnaflux Corp. under the trade name of "Zyglo." Zyglo is an entirely different, *non-magnetic* inspection method particularly suited for the detection of cracks and other surface discontinuities in aluminum, magnesium, austenitic steels and other non-magnetic materials. It employs fluorescent liquid penetrants and black light, and the indications look similar to those formed by Magnaglo, but there the similarity ends.

ELECTRIC SHIP PROPULSION.—The following summarization of the views of B. Bleicken, superintendent engineer of the Hamburg American Line, as regards future types of ship propulsion, was translated and published by The British Motor Ship, August, 1942.

In Germany recently B. Bleicken, the superintendent engineer of the Hamburg American Line, has given at considerable length his views on the

subject of the types of machinery for ship propulsion in the future, based upon the experience gained by the Hamburg American Line with propulsion by Diesel engines (with direct-drive electric transmission or gearing), also with steam turbines. As might be anticipated, the electric system is favored, since the last dozen of the Hamburg American Line's fleet of over 100 vessels are propelled electrically, and it had been stated officially that the owners had decided to adopt this system for all their future tonnage. Some valuable figures relating to costs of running oil-fired steamers and motor ships both with electric propulsion and direct drive are given, also a proposal for employing new types of machinery, including the two-stroke Sulzer supercharged engine with exhaust turbine. Evidences of new development in Germany are given, and from these various aspects Mr. Bleicken's views are of considerable interest. They are translated and summarized in the following article:—

The development of Diesel propulsion involving higher powers called for new systems to be employed. In the first place, gearing was utilized, allowing high revolution engines to be adopted, and many such plants have given years of reliable service. Even more reliable, but dearer and requiring greater space, is the provision of hydraulic drive. Originally, this was constructed with ahead and astern rotors, so that it was unnecessary to have reversible engines. Later this has been given up, and hydraulic transmission used merely as a flexible coupling. With this arrangement high-speed engines and reduction gearing are still utilized.

Another system which was first employed by the Hamburg American Line is Diesel-electric transmission by alternating current. The advantage is that with several generating sets the power for propulsion can be chosen according to requirements, and a short engine-room suffices. For instance, in Hamburg American Line ships an installation of 14,000 Bhp. occupies a very short machinery space. In the case of ships engaged on certain routes there are special advantages, as on the trade to Australia. On the outward journey the speed is 13½ knots, whereas on the return run a speed of 15 knots is needed. The outward run, therefore, requires only two-thirds of the power of the homeward voyage, with the result that one of the three generators may be shut down for the whole period, and this allows overhaul to be carried out while the vessel is under way. This is preferable to carrying out the work in more strenuous circumstances in harbor. Moreover, the engine-room staff is then free while the vessel is in port, and the value of this leisure is obvious in the maintenance of high standards of morale.

A step farther has been made by employing alternating current also for the auxiliary services. The advantages are numerous. The a.c. motor is much more reliable and robust than the d.c. machine. For the Hapag ships' plant slip-ring motors are avoided. As marine engineers and electricians know, most of the electrical work on board is on account of slip rings, which must be maintained in a clean condition, must frequently be trued up, and the brushes must be continually inspected.

Moreover, it is an advantage if the starter can be eliminated and the speed of revolution increased. The price of a short-circuited rotor is 42 per cent of a d.c. armature, and there is a diminution in the amount of copper required. The necessity of avoiding sparks is specially important. Higher voltages can be employed, and in the main circuit we are already adopting 5000 volts. For the smaller motors driving the auxiliary machinery voltages of 500 are used. The price of the switchgear is lower than with 220-volt d.c., whilst the cost of the cables is no higher than with the d.c. installation. An important fact is the smaller danger of fire with a.c. current. Although d.c. motors are more easily regulated, this is not of much importance so far as merchant ships are concerned. Unfortunately, it is a dis-

advantage that cargo winch a.c. motors must be regulated on the Ward-Leonard system, which is dearer than the direct contactor system of the d.c. motors; but it is anticipated that this disadvantage will be overcome in the near future, and that contactor controllers may be employed for a.c. winch motors. Contrary to the conditions with direct current motors, the a.c. system does not affect the ship's compass, and the influence on the wireless equipment is smaller than with direct current motors.

The a.c. installation must be more carefully calculated than is necessary with direct current. The generators on board vary between 100 and 500 Kw., and the largest current user requires about one-quarter of this figure. For example, we know not only the quantity of cooling water needed, but also the anticipated resistance. The same applies to other auxiliary machinery, since sufficient experience has been gained. The motors can, therefore, be very closely designed.

The following may be taken as the advantages and disadvantages of alternating current for ship use:—

Disadvantages.

1. More severe effect of electric shock on the human body.
2. Greater difficulty in regulation.

Advantages.

1. Potentially higher voltage with correspondingly reduced weight of copper.
2. Reduced danger of fire.
3. Simpler construction of generators and motors.
4. Absence of sparks.
5. High revolution speed and low weight.
6. Low price.
7. Ready availability.
8. Reliability in spite of severe handling.
9. Less liability to explosion, which is important for tankers.
10. No equalizing wires needed; easy transformation of voltage.
11. No influence on the compass.
12. No disturbance of the wireless system.

The replacement of direct current by alternating current on board ship is a step forward. The safety of ships is increased, and the work required on board is diminished.

Figure 1 shows the comparison between the prices of direct current and alternating current motors.

In order to supply a picture of the tendencies in fuel prices and machinery types it is of interest to give the cost of fuel per 1000 Bhp. per hour, as ascertained from the performance of ships in the Hapag's fleet. In Table I are shown the average prices for coal, bunker oil, Diesel oil and gas oil paid by the Hamburg American Line in the year 1938-9. The total quantities and mean prices are shown in Table II.

The very wide variation in prices of all classes of fuel will be noted. The cost of fuel per 1000 Bhp. per hour is given in Table III. The coal-fired ships are the most expensive. They are usually not equipped with the most up-to-date installations, as the tendency of late years has been towards the adoption of higher steam pressures, and it is preferred to employ oil-fired boilers with these. Moreover, coal occupies much more space per ton than oil, and the calorific value is 7000, compared with 10,000. The coal must be carried above the double bottom, and thus occupies a part of the cargo space. Oil for the most part can be bunkered in double-bottom

tanks. Naturally, it would be desirable if German-mined coal could be widely used on board ships. It seems, however, doubtful in view of the great advantages of oil, particularly for ocean-going vessels, whether this can be continued.

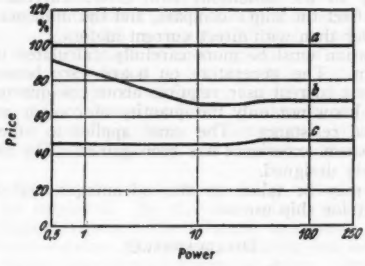


FIGURE 1.—COMPARISON OF PRICES OF DIRECT AND ALTERNATING CURRENT MOTORS.

a, Direct Current; *b*, Commutator, Alternating Current; *c*, Induction Motors.

TABLE I.—AVERAGE PRICE OF FUEL PER TON (RM), AT VARIOUS PORTS (1938/1939).

Bunkering Port	Coal	Bunker Oil	Diesel Oil	Gas Oil
Newcastle-on-Tyne	8.21	—	—	—
Greenock	11.65	—	—	—
Antwerp	12.02	—	—	36.14
Dairen	12.24	—	—	—
Rotterdam	12.26	19.16	—	34.40
Hamburg	12.40	19.23	29.32	32.06
Norfolk	13.13	—	—	—
New York	15.83	15.80	31.85	—
Shanghai	14.41	—	31.77	—
Singapore	16.08	25.05	30.04	—
Hongkong	16.24	—	31.75	39.20
Colombo	17.02	25.50	—	53.11
Las Palmas	18.49	—	28.29	34.14
London	18.54	—	—	—
Colon	18.73	16.32	30.75	33.44
Port Said	19.17	21.01	28.87	34.39
Port Sudan	19.62	21.01	29.51	—
Curacao	—	12.71	—	29.94
Balboa	—	15.87	—	33.11
Miri	—	21.30	26.44	—
Kobe	—	27.13	33.00	—
Los Angeles	—	15.02	27.03	27.03
Yokohama	—	—	31.51	—
Sydney	—	—	37.98	—
Valparaiso	—	—	61.65	—

Considerable reductions in weight of machinery are to be anticipated by the adoption of higher speed. Only a few years before the war Diesel engines were built weighing 160 Kg. per Bhp. (350 pounds). Now it is possible to construct them with a weight of 8 to 10 Kg. per Bhp. (17 to 22 pounds). Even allowing 25 Kg. per Bhp. (55 pounds), there would be

TABLE II.—PRICES PAID FOR VARIOUS FUELS AND TOTAL QUANTITY PURCHASED BY HAPAG IN 1938-9.

Coal		Bunker Oil		Diesel Oil		Gas Oil	
Quantity tons	Price per ton RM.	Quantity tons	Price per ton RM.	Quantity tons	Price per ton RM.	Quantity tons	Price per ton RM.
306,677	13.49	160,066	16.45	57,405	28.41	65,018	32.62

TABLE III.—FUEL COSTS FOR VARIOUS SHIPS IN 1938/1939, IN DOLLARS PER 1000 BHP. HOURS.

Name of Ship	Type	Gross Tons	Fuel	Average cost per 1,000 b.h.p. hrs.
"Hamburg"	S	22,117	95 per cent. fuel oil, 5 per cent. gas oil	1.85
"Hansa"	S	21,131	Fuel oil	1.87
"Iberia"	M	9,829	Gas oil	2.05
"Heidelberg"	M	692	Diesel oil	2.10
"Tacoma"	S	8,268	95 per cent. Diesel oil, 5 per cent. gas oil	2.10
"Duisburg"	M	7,389	75 per cent. Diesel oil, 25 per cent. gas oil	2.11
"Seattle"	M	7,000	Gas oil	2.14
"Oakland"	M	6,757	90 per cent. gas oil, 10 per cent. Diesel oil	2.16
"Huascaran"	E	6,951	Gas oil	2.22
"Cordillera"	M	12,055	Gas oil	2.23
"Palatia"	M	3,979	40 per cent. gas oil, 60 per cent. Diesel oil	2.30
"Ramses"	M	7,983	75 per cent. Diesel oil, 25 per cent. gas oil	2.32
"Wuppertal"	E	6,737	95 per cent. gas oil, 5 per cent. Diesel oil	2.44
"Patria"	E	16,595	80 per cent. gas oil, 20 per cent. Diesel oil	2.45
"Leuna"	S	6,856	Coal	2.63
"Magdeburg"	M	6,218	Gas oil	2.66
"Osorno"	E	6,951	Gas oil	2.66
"Roda"	M	6,780	75 per cent. gas oil, 25 per cent. Diesel oil	2.69
"Bochum"	S	6,121	Coal	2.74
"Uckermark"	S	7,021	Fuel oil	2.83
"Hanseat"	S	8,241	95 per cent. fuel oil, 5 per cent. gas oil	2.83
"Adalia"	S	3,199	Coal	2.83
"Ammon"	S	7,134	Coal	2.89
"Bitterfeld"	S	7,659	Coal	2.85
"Kellerwald"	S	5,032	Coal	2.87
"Nordmark"	S	1,060	95 per cent. coal, 5 per cent. gas oil	3.01
"Hamm"	S	5,874	Coal	3.30
"Kurmark"	S	7,021	95 per cent. fuel oil, 5 per cent. gas oil	3.36
"Hindenburg"	S	7,880	Coal	3.35
"Saarland"	S	6,725	Coal	3.61
"Sesostris"	S	2,013	Coal	3.65
"Neumark"	S	7,851	Fuel oil	3.70
"Oldenburg"	S	8,537	Coal	4.22

Note.—S—Steamer. M—Motor ship with direct or geared drive. E—Motor ship with electric drive. $1—2.493 RM.

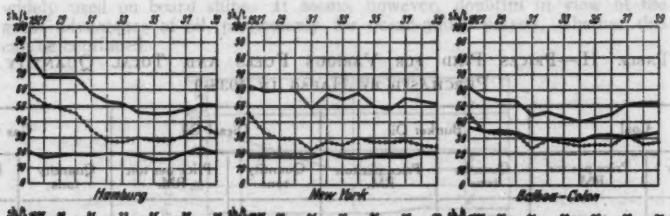


FIGURE 2.—PRICE CHANGES IN DIESEL OIL, FUEL OIL AND COAL.

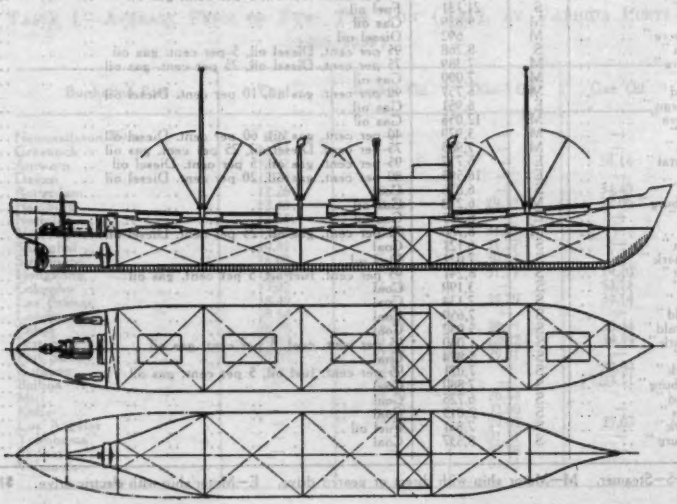


FIGURE 3.—PROPOSED 9000-TON 13.5-KNOT ELECTRIC SHIP WITH SULZER OPPOSED-PISTON SUPERCHARGED ENGINES WITH EXHAUST TURBINE.

a saving of 500 tons over a normal 12,000 Bhp. Burmeister and Wain installation which weighs 80 Kg. per Bhp. Not only is the weight reduced, but the height is lower. In this direction Diesel electric propulsion shows itself to great advantage, and will, no doubt, be widely adopted in the future.

The trends of the quotations for coal and oil are illustrated in Figure 2.

Figure 3 shows sketch plans of a proposed 9000-ton ship with a speed of 13.5 knots, having machinery of 3800 Bhp. An opposed-piston Sulzer supercharged Diesel engine with exhaust turbine is employed. It is fully balanced and runs at 450 Rpm., the cylinder diameter being 300 millimeters and the piston stroke 450 millimeters. The engine is conveniently installed with the generator in a compartment above the propelling motor. The necessary space is very small compared with all other machinery proposals for such a ship, since the compartment which it occupies is unsuitable for general cargo, and the faster the ship the finer are the lines. It is not a fixed rule that the engine-room should occupy the best cargo space. That may be necessary with coal firing, since with empty bunkers and a light ship the right trim could not otherwise easily be attained.

In all tankers we have broken away from this idea. With the electric drive there is the advantage that the main machinery can be arranged in the most favorable position. In the proposal in Figure 3 it is installed within the height of the main deck, this being due to the fact that the cylinders are horizontal. The propelling motor is installed below in a compartment which, in any case, could not be utilized for freight. The total machinery space does not now approach the 13 per cent of the gross capacity allowed under the Classification rules. This is one reason more for this foolish regulation to be scrapped. Fortunately, German owners are at last unanimous in insisting that after the war, under all conditions, such a rule shall not be perpetuated.

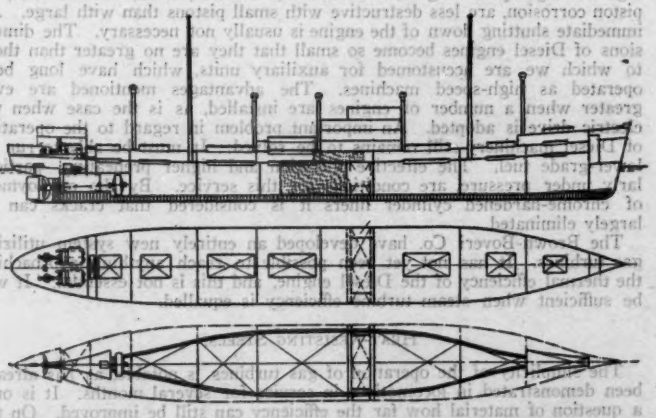


FIGURE 4.—PROPOSED 9000-TON 16-KNOT ELECTRIC SHIP WITH TWIN-SCREW 8000 BHP. MACHINERY, UTILIZING TWO-STROKE PRESSURE-CHARGED ENGINES INSTALLED ABOVE THE PROPELLING MOTOR COMPARTMENT.

Figure 4 shows a 9000-ton ship designed for a speed of 16 knots. In this case, also, Sulzer two-stroke supercharged engines are installed, two of 4000 Bhp. being fitted, with a cylinder diameter of 300 millimeters and a piston stroke of 450 millimeters. By this design a space of 2500 cubic meters amidships, ordinarily occupied by the engine-room, is freed for cargo.

On the subject of engine-room staff opinions differ widely. Many owners fear a shortage of capable and trained personnel after the war, and for this reason would have the simplest machinery installation, i.e., reciprocating steam engines with coal-firing and hand-fired boilers. The writer takes the opposite view. There is no "simple" installation considered from the point of view of the personnel. It seems that it is simplicity in operation which is needed. A completely automatic refrigerating installation, for instance, comprises many complicated technical elements, but these are there in order to ensure simple operation. And it is similar in a ship.

So far as steam machinery is concerned, the steam turbine is more suitable than the reciprocating engine. The steam consumption of a modern turbine installation is lower even with such moderate powers as 2000 Bhp. Weight, price and space requirements are less. The turbine is simpler in operation, and the higher revolutions are even an advantage when a propeller may break. In ocean-going ships the reciprocating steam engine will steadily be replaced, and for boilers mechanical stoking must come into general use.

The quality of materials has greatly benefited by the war. The smaller the individual parts of an engine, the more completely can the various tests on the material be carried out. In modern workshop practice it is possible to manufacture small parts with the greatest precision, more easily than corresponding parts of heavier machines. The weights are lower and the parts can more easily be handled. All of this tends to indicate the advantage of high-speed engines. Moreover, troubles, such, for instance, as piston corrosion, are less destructive with small pistons than with large. An immediate shutting down of the engine is usually not necessary. The dimensions of Diesel engines become so small that they are no greater than those to which we are accustomed for auxiliary units, which have long been operated as high-speed machines. The advantages mentioned are even greater when a number of engines are installed, as is the case when the electric drive is adopted. An important problem in regard to the operation of Diesel machinery still remains to be solved. It must be able to run on lower-grade fuel. The effective filtration and higher preheating, particularly under pressure, are conditions for this service. By the employment of chrome-hardened cylinder liners it is considered that cracks can be largely eliminated.

The Brown-Boveri Co. have developed an entirely new system utilizing gas turbines. It has not yet been possible to reach anything approaching the thermal efficiency of the Diesel engine, and this is not essential. It will be sufficient when steam turbine efficiency is equalled.

Heat-Resisting Steels.

The simplicity of the operation of gas turbines is notable, as has already been demonstrated in locomotives in service for several months. It is only a question of material how far the efficiency can still be improved. On the problem of heat-resisting steels, several manufacturers are now intensively engaged. The great advantage of the gas turbine is that it can employ the lowest grade oil, and that it operates with a very great excess of air.

As bunker fuel oil is cheaper than Diesel oil, it appears that even in marine propulsion the gas turbine will be developed. The weight and space

required for an installation of this character are relatively small. For ships, gas turbines can most satisfactorily be utilized in conjunction with electric transmission, since it is then unnecessary to arrange for astern turbines.

SODIUM LIGHT FOR MICROSCOPIC FLAW DETECTION.—The Current Topics section of the November, 1942, Journal of the Franklin Institute is the source of this note. The reader's attention is also invited to the article on fluorescent magnetic detection, also reprinted in this issue.

Sodium light, which has proved so effective in the prevention of night traffic accidents, is being used in several important war plants for surface inspection by microscope, because of its efficiency in the detection of pits, cracks, and flaws in materials. The sodium lamp is essentially an arc lamp, and differs from the incandescent in that it requires a special socket and individual control for each lamp. The unusual perception of detail under sodium illumination is due to the monochromatic nature of the light, according to H. A. Breeding, of the General Electric Illuminating Laboratory. The eye, in common with other lenses, actually focuses only one narrow wave or color band at a time. Other colors in the beam tend to fog the picture. Thus, minute details may be lost in examining an object under a light which contains all wave bands, in contrast to an examination of the same object under monochromatic light which contains only one wavelength. "Probably because people through the centuries have looked at more green and yellow-green objects than those of any other color," Mr. Breeding explains, "the eye has gradually developed an affinity for light in this color band. Sodium light is golden yellow and very near the region of yellow-green in the spectrum where maximum eye sensitivity occurs. A given amount of energy from sodium light produces several times as much illumination as the same amount of energy in white light." As in the case of sodium lighting for night safety driving, monochromatic light for microscopic inspection is most effective when spread uniformly over a large area rather than concentrated in small bright patches. In this way an undistorted view of both size and shape of flaws present is obtained. For most effective results, the level of illumination should be comparatively high, especially when the contrast between flaw and surrounding material is low. It is helpful in searching for cracks and blow holes to treat the part with either a light-absorbing or light-reflecting dye, the dye depending on the nature of the surface to be inspected. The dyed surface should be cleaned thoroughly before inspection. This procedure increases the contrast between the flaw and object to the point where many times smaller flaws can be detected. In all cases it has been found necessary to block out as much sunlight as possible in order not to destroy the monochromatic nature of the sodium illumination.

BOUNCELESS BALLS ILLUSTRATE PRINCIPLE.—This brief note is reprinted from the September, 1942, issue of Metals and Alloys.

Westinghouse engineers have found that a steel ball half-filled with metallic powder will not bounce, as this time-exposure photograph illustrates. Two balls of the same weight—one empty and one containing powder—were dropped simultaneously from the top of the posts, to the left.

The empty ball left a looping trail of light as it bounced four times on the steel plate. The ball containing the powder rolled without bouncing, as shown by the straight streak of light on the plate. Rough surfaces of the metal powder particles created frictional heat, as they slid over each other, dissipating the energy the ball would have used in bouncing, the engineers explained.

This discovery has been used to prevent poor connections by eliminating bouncing and chattering in electrical relays—delicate, swift-acting switching devices used in communications systems. The relay contacts are made hollow and partly filled with powder, or special hollow powder containers are attached to the contacts.

BOOK REVIEWS.

POPULAR MATHEMATICS, By Demming Miller. Published by Coward-McCann, Inc., 2 West 45th St., New York City. $3.75.

The author, in 616 pages, writes an enjoyably readable book which expounds, in order, arithmetic, geometry, algebra, analytic geometry, trigonometry, conic sections, solid geometry and spherical trigonometry, and calculus. The reader is led from one to the other and given a clear understanding of the methods of use of each and the connection of one to another.

For one who has studied all of these subjects, the book is an excellent review which in addition gives an entirely different concept of the subject than the one retained after having studied each of the branches in the conventional manner. The book contains everything necessary to a complete understanding of mathematics, if used as a primary text book itself.

Interspersed throughout is the history of the development mathematics presented in relation to the mathematics itself. The author uses a humorous style which might well be incorporated into grade and high school courses to help to furnish a student with a better understanding of mathematics as the valuable tool it is instead of the dose which is to be shunned.

"Popular Mathematics" as a text book, presented with understanding should succeed in making mathematics popular.

QUESTIONS AND ANSWERS FOR MARINE ENGINEERS. Book II—Engines. Marine Engineering and Shipping Review. Published by Simmons-Boardman Publishing Corporation, New York. Compiled by Capt. H. C. Dinger, U.S.N. (Ret.)

Here in a small paper-bound book of 180 pages, presented in question and answer form is a guide book for the operating engineer in the engine room of a ship. This follows a previous volume which covered the boiler room.

OTHER BOOKS RECEIVED.

EASY MALAY WORDS AND PHRASES, By Marcus A. Mendlesen. Published by John Day Company, Inc., 2 West 45th St., New York, N. Y. $1.00.

ASSOCIATION NOTES.

Election of Officers.

The following have been elected officers of the Society for the calendar year 1943:

President:
Rear Admiral J. J. Broshek, U. S. N.

Secretary-Treasurer:
Captain J. E. Hamilton, U. S. N.

Member of Council:
Rear Admiral E. L. Cochrane, U. S. N.
Rear Admiral E. W. Mills, U. S. N.
Rear Admiral C. L. Brand, U. S. N.
Captain L. F. Small, U. S. N.
Captain J. N. Heiner, U. S. C. G.
Mr. A. F. E. Horn.
Mr. D. S. Brierley.

Membership.

The following have joined the Society since the publication of the November, 1942, Journal:

Naval.

Atwood, David L., Ensign, U. S. N., U. S. Proving Ground, Dahlgren, Va.

Barnum, Charles N., Lieut., U. S. N. R., 540 N. 8th St., Manitowoc, Wis.

Bohjelian, Albert G., Ensign, U. S. N. R., 6203 Chestnut St., Philadelphia, Pa.

Cash, James B., Lieut., U. S. N. (Ret.), Naval Training School (Aviation Maintenance), Norma, Okla.

Genther, J. E., Ensign, U. S. N. R., Navy Section Base, Portland, Me.

Harpster, David L., Ensign, U. S. N. R.

Haynes, R. A., Lieut., U. S. N. R.

Heinrich, Edward E., Commander, U. S. N. R.

Hertz, David Bendel, Lieut., U. S. N. R., 285 Central Park, West, New York, N. Y.

Holm, Russell H., Ensign, U. S. N. R.

Kegley, Frank T., Lieut. Commander, U. S. N. R.. Architectural Engr. Partner, Walton & Kegley, Evanston, Ill. Mail 2646 Broadway Ave., Evanston, Ill.

Kinert, David F., Lieut. Commander, U. S. N.

Knight, J. B., Lieut. Commander, U. S. N., O. I. C. Underwater Sound Laboratory, Fort Trumbull, New London, Conn. Mail, Box 108, Niantic, Conn.

MacCormack, John S., Ensign, U. S. C. G., Coast Guard, San Juan, P. R.

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Mitchell, William B., Lieut., U. S. N. R., care Supervisor of Shipbuilding, San Pedro, Calif.

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Verrell, Harold, Lieut., U. S. N., 2358 Northland Ave., Lakewood, Ohio.

Wengland, C. Edward, Ensign, U. S. N. R., Box WD 49, 15th Naval District, Balboa, C. Z.

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Hobbs, J. E., Engineering Consultant, Gibbs & Cox, 1 Broadway, New York, N. Y.

Jenkins, James W., Senior Engineer, Materials, Bureau of Ships, Navy Department.

Whitney, C. F., Principal Engineer, Electrical, Bureau of Ships, Navy Department. Mail, 5504 Wriley Road, Friendship, Washington, D. C.

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McGarvey, J. R., Consulting Engineer, Don Caffery Glassie Co., 212 Munsey Building, Washington, D. C.

Reinmann, Leonardo, Capt. Corbets Ing., Acorazado "Latorre," Valparaiso, Chile.